

COMPARING THE PERFORMANCE OF TWO COMMERCIAL SALMON MANAGEMENT  
STRATEGIES USING RUN RECONSTRUCTION AND MODEL SIMULATIONS


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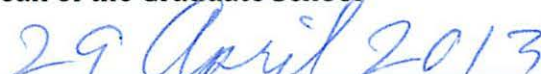
  
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STRATEGIES USING RUN RECONSTRUCTION AND MODEL SIMULATIONS

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## **Abstract**

Two commercial salmon management strategies currently being used in Alaska are management by emergency order opening ("active management") and, to the extent practical, a fixed fishing schedule. Active management is more expensive than a fixed fishing schedule. The objective of this thesis is to compare the performance of the two management strategies on the Egegik and Togiak fisheries in Bristol Bay, Alaska. To accomplish this, we reconstructed the sockeye salmon (*Oncorhynchus nerka*) runs to Egegik and Togiak and then simulated the management strategies on each fishery. Active management resulted in higher yearly catches, a higher percentage of the run caught, less yearly variation in escapement, and less years of escapement below the goal range. A fixed fishing schedule resulted in less yearly variation in catch and a more even harvest rate. Potential benefits of active management are that maximum sustained yield is more likely to be achieved, under escapement is less likely, and the productive capacity of the fishery is better protected. Potential benefits of a fixed fishing schedule are lower management costs, better maintenance of the genetic and phenotypic diversity and sex ratio, and more predictability for fishermen and processors.

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## Introduction

Bristol Bay, located in southwest Alaska, is one of the most important commercial salmon fisheries in the world, averaging an annual catch of 25.8 million sockeye salmon (*Oncorhynchus nerka*) from 1990-2009 (Salomone et al. 2011). The commercial harvest is variable from year to year, ranging from a low of 1.5 million in 1973 to a high of 45 million in 1995. Commercial fishing in Bristol Bay occurs in five separate districts: the Ugashik, Egegik, Naknek-Kvichak, Nushagak, and Togiak. Variability among these individual stock runs makes matters more complicated; the overall Bay run size may be down, even while the run to a specific river may increase (Hilborn et al. 2003).

Two of the considerations for managing the commercial fishery are the number of people involved in the fishery and the importance of the fishery to the local and regional economy (State of Alaska 2010, provision AS 16.05.251). In numerous Alaskan communities, the salmon fishery is the largest part of the economy. For example, over half of the workforce in the Aleutians and Bristol Bay is involved in the salmon harvest or processing industry (Robards and Greenberg 2007; Warren 2010). Increasing the number of people involved in a fishery provides greater employment opportunities; however, increased participation may lower the profit per person (Link et al. 2003, Hilborn et al. 2005). Both increased participation and increased profit may improve the local economy, but to what extent varies by location.

Two management strategies currently being used in Bristol Bay are emergency order openings or "active management" (e.g., the Egegik fishing district, Clark et al. 2006) and, to the extent practical, a fixed fishing schedule (e.g., the Togiak fishing district, State of Alaska, provision 5AAC 06.369). The use of emergency order openings affords managers greater control of escapement, as well as the ability to maximize commercial harvest; however, the necessary in-season monitoring is labor intensive and very expensive. A fixed fishing schedule would allow for budget resources to be saved by using less intense monitoring. In the case of low-value salmon fisheries or in times of budget crisis, it does not make economic sense to have a high expenditure. The excess funds could either be used for high-value salmon fisheries or saved in the budget.

Measuring escapement will be more difficult for a fixed fishing schedule if in-season monitoring is stopped. The recruits from a particular year of spawners do not return until years after emergence, meaning there would be a time lag between years of low escapement and observing its effects. In addition, recruits from a particular year of spawners do not all return the same year (except in pink salmon), making it more difficult to determine the exact return from each year of spawners (Quinn 2005).

In the absence of in-season monitoring techniques, an escapement estimate can be made from catch-per-unit-effort (CPUE) using a power curve relationship, like that developed for the Togiak River (Brannian 1982). For this application, the effort of landings is raised to a power to calculate the catchability co-efficient, which

is inversely proportional to escapement. Brannian (1982) found that the best application is to use cumulative escapement instead of daily escapement.

Inaccurate and underreporting of catch is a major concern for this type of in-season escapement estimate.

The objective of this thesis is to contrast the costs and benefits of management by emergency order openings and a fixed fishing schedule on the Egegik and Togiak sockeye salmon fisheries from 1986-2010. In particular, I examine how these strategies affect the economics of the fishery and how they meet the requirements of Alaska's salmon management policies. In chapter 1, we develop run reconstructions for each fishing district to estimate the daily arrivals of sockeye and of other parameter values relevant to the salmon runs and commercial fisheries. In chapter 2, we simulate management by emergency order openings and a fixed fishing schedule on the Egegik and Togiak fisheries using these parameter estimates. These techniques allow us to compare the differences between management by emergency order openings, a fixed fishing schedule, and the historical strategy, within each fishing district. The performance of a management strategy is dependent on the attributes of the particular fishing district. We develop a list of attributes of a fishery conducive to each management strategy.

## Chapter 1:

### Evaluating the Performance of Two Salmon Management Strategies using Run Reconstruction<sup>1</sup>

#### Abstract

Commercial salmon fisheries in Alaska are managed to obtain escapement goals within a fixed range, while attempting to maximize sustained yield. Two management strategies currently being used are: i) emergency order authority and ii) a fixed fishing schedule. In this paper, we analyze and contrast the historical performance of these two management strategies in the Egegik and Togiak sockeye salmon *Oncorhynchus nerka* fisheries in Bristol Bay, Alaska. To accomplish this, we reconstructed the daily runs to each river through the use of catch, effort, and tower count data. Our results show that management by emergency order openings resulted in a higher percentage of returning fish caught, less yearly variation in escapement, and escapements that were always above the minimum escapement goal. A fixed fishing schedule resulted in less yearly variation in catch and a harvest rate spread more evenly throughout the run. This more even harvest rate likely better protects substocks and the sex ratio. Emergency order authority affords a manager more control over the fishery, but requires more informative data. A fixed

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<sup>1</sup> Carney, J. M., and M. D. Adkison. 2013. Evaluating the performance of two salmon management strategies using run reconstruction. Submitted to North American Journal of Fisheries Management.

fishing schedule provides more predictable catch, but carries a higher risk of over-harvest. Both management strategies were successful and were suited to the circumstances of their fishery.

## Introduction

Pacific salmon *Oncorhynchus spp.* have a complex life history. Most salmon return to freshwater to spawn after spending at least one year feeding in marine waters (Quinn 2005). Salmon home to their natal river with high fidelity, generally 95-99%, creating separate stocks of salmon based on spawning location (Dittman and Quinn 1996; Quinn 2005). Furthermore, the salmon returning to a particular location may be comprised of substocks that differ in spawn timing (Gharrett et al. 2001; Hendry and Day 2005). Arrival to spawning locations also differs between sexes, as males tend to arrive earlier than females (Morbey 2000). The productivity of salmon stocks varies greatly from year to year, making the number of fish returning difficult to predict (Quinn and Deriso 1999; Hilborn et al. 2003).

The complex life history of salmon complicates management of salmon fisheries. Most salmon fisheries are terminal fisheries, in which fishing fleets capture salmon in estuaries and river mouths as they migrate to their spawning locations. A particular fishery can be comprised of multiple stocks, since each river, lake, and tributary in the watershed could represent a different spawning location. Managers must manage the fishery to protect these multiple stocks. Stocks may also be subdivided based on spawn timing, so harvest and escapement should be spread



throughout the season. However, as the number of fish returning is largely unpredictable, harvest rates frequently change drastically from the early to mid-season, as an unusually small or large return becomes apparent.

Salmon fisheries in Alaska are managed to obtain escapement within a fixed range, while attempting to maximize sustained yield (State of Alaska 2001). The Alaska state constitution states that natural resources, including salmon, are to be "utiliz[ed], develop[ed], and conserv[ed]...for the maximum benefit of its people" and are to be maintained on the "sustained yield principle" (Clark et al. 2006). Maximum sustained yield is the highest amount that can be harvested without negatively affecting future harvests (Quinn and Deriso 1999).

Two separate governing bodies control conservation and allocation issues. Fisheries professionals at the Alaska Department of Fish & Game (ADF&G) are tasked with determining the number of fish needed to spawn to achieve maximum sustained yield, which is the recommended escapement goal. The Alaska Board of Fisheries is tasked with how to allocate the surplus, and in some cases can choose a different goal (Policy for the Management of Sustainable Salmon Fisheries). In addition to ecological and biological conservation concerns, managers must consider the social and economic effects on local, fisheries-dependent communities. In numerous Alaskan communities, the salmon fishery is the largest part of the economy of the local community; for example, over half of the workforce in the Aleutians and Bristol Bay is involved in the salmon harvest or processing industry (Robards and Greenberg 2007; Warren 2010).

Emergency order authority is the most common tool used to manage salmon fisheries in Alaska. Managers of such fisheries open and close the commercial fisheries based on estimates of the current year's escapement and run strength in relation to what is needed to meet the final escapement goal (Clark et al. 2006). At the beginning of the season, average run timing from previous years figures heavily in setting fisheries openings; run timing is a measure of the percentage of the total return expected by date. Tower counts, aerial surveys, weirs, and sonar scans of escapement are used along with test fishing (fishing vessels that catch salmon before they arrive at the fishing districts), catch analysis, and age composition of samples to continuously update the estimated run strength and timing used to determine fishery openings. In-season genetic analyses have recently been employed in several salmon fisheries, by air lifting samples to a genetics laboratory in Anchorage to determine the proportion of catches heading to particular fishing districts (Dann et al. 2009). This emergency order management of fishing makes fine control of escapement possible for managers. However, the necessary in-season monitoring of run strength is labor intensive and very expensive.

An alternative to management by emergency order is a fixed fishing schedule, where fishing openings and closures are preset. Although Alaskan fisheries are managed to obtain a fixed escapement range, to the extent practical some areas are managed with a fixed fishing schedule throughout the season (e.g., the Togiak River), while other areas use it early in the season (State of Alaska 1996; Clark et al. 2006). Allowing fishing for a fixed number of days per week provides a

more stable commercial fishery by allowing a more constant harvest of fish, whereas harvest is more variable and dependent on run strength with management by emergency order (Steiner et al. 2011). Due to the set fishing closures in a fixed fishing schedule, fleet harvest and processing limitations would be exceeded less often during strong runs than with management by emergency order. Although the maximum commercial catch would be reached by meeting the fixed escapement goal, a larger economic profit from the fishery could be attained by a fixed fishing schedule since it would allow harvest even when the escapement goal was not met (Bue et al. 2008). However, the stock of fish may not be as well protected if fish are harvested when the escapement goal is not met.

Balancing harvest and escapement is a major challenge facing fisheries managers; a condensed run timing in Bristol Bay, Alaska complicates this problem. Although escapement is the first priority (State of Alaska 2001), fishery managers need to make decisions that will protect the fish stock (i.e., escapement), while providing vital economic support for the local community. The majority of the Bristol Bay sockeye *Oncorhynchus nerka* run occurs over a three to four week time span, from late June to mid July (Westing et al. 2006). A variation of even a few days in run timing could negatively affect harvest and/or escapement totals. High numbers of fish returning at the beginning of the season due to an early run timing could be mistaken for a stronger run, which would lead to over-harvest. A late run timing could lead to the opposite outcome. If managers had known the optimum

escapements and the inter-annual variation in run sizes, there could have been a significantly larger salmon catch in Bristol Bay since 1950 (Martell et al. 2008).

### *Run Reconstructions*

Run reconstructions are a useful tool for comparing different management strategies. Run reconstructions use catch and escapement data to calculate run timing and abundance of fish arrivals (Starr and Hilborn 1988; Templin et al. 1996). Comparing the catch data to the estimated run size allows the proportion of returning fish caught by the fishery to be estimated, and inclusion of effort data provides an estimate of the fishing fleet efficiency. The harvest rate of the fishery and how it changes throughout the season is calculated from estimated daily arrivals and escapements. Reconstructing the runs from multiple years yields an estimate of the annual variation in run size and timing, allowing a comparison of the performance of management strategies under a variety of circumstances.

This paper analyzes the historical performance of management by emergency order on the Egegik sockeye salmon fishery and of a fixed fishing schedule on the Togiak sockeye salmon fishery from 1986-2010. By reconstructing the daily arrivals to the fisheries we can compare the differences between the two areas, the results of the management strategies, and how the area and strategy affect each other. Desirable attributes of a management strategy are a high mean and low coefficient of variation (CV, defined as  $SD/mean$ ) of catch, low frequency of escapement below the ADF&G goal range, and a harvest rate evenly spread throughout the run. Our objective was to explore the costs and benefits associated

with each management strategy and the appropriateness of each strategy for its fishing district.

## Materials and Methods

### *Study Site*

Bristol Bay, located in southwest Alaska, is one of the most important commercial salmon fisheries in the world, averaging 25.8 million sockeye salmon caught annually from 1990-2009 (Salomone et al. 2011). The commercial harvest is variable from year to year, ranging from a low of 1.5 million in 1973 to a high of 45 million in 1995. Variability among individual stock runs makes matters more complicated; the overall run size may be down, even while the run to a specific river may increase (Hilborn et al. 2003).

Commercial fishing in Bristol Bay occurs in five separate districts: the Ugashik, Egegik, Naknek-Kvichak, Nushagak, and Togiak (Figure 1.1). The Egegik and Togiak fisheries are ideal locations for our study because they are managed with contrasting strategies and they each have only one major river system that sockeye salmon return to (the Egegik and Togiak Rivers, respectively). Within each river, substocks are separated by run timing and spawning location, e.g., beach vs. tributary spawner (Habicht et al. 2007; Dann et al. 2009). Although both districts are managed to attain escapement goals, commercial fishing in the Egegik District is managed by extensive use of emergency order openings, whereas the Togiak District is managed with a fixed fishing schedule as much as possible. The

escapement goal range is 800,000 to 1,400,000 in tower counts for the Egegik River, while the Togiak goal is 100,000 to 250,000 in tower counts plus 20,000 fish spawning below the counting tower.

### *Data*

Daily catch and effort data from the ADF&G fish ticket database (the database) were provided by Paul Salomone (ADF&G, Anchorage). When a drift gillnet vessel or set gillnet operator delivered fish to a processor, the number of fish caught, the date of the fishing opening, the date of delivery, and the unique drift vessel or set gillnet permit number was recorded in the database. A query of the database reported the sum of the catch broken out by fishing date, delivery date, and gear type (drift gillnet or set gillnet). Each record from the query also included the number of unique drift vessels or the number of unique set gillnet permits that delivered fish (we could not get the unique vessel and permit numbers due to confidentiality restrictions). To calculate the daily drift gillnet or set gillnet catch, we summed catches from all delivery dates for a single date fished.

Drift gillnet effort was calculated from the database as the number of drift vessels that fished each day (in preliminary explorations we found that the length of the fisheries openings had little effect on harvest rates - see below). When there was only one delivery date for a single date fished, the daily drift gillnet effort was equal to the number of unique drift vessels recorded by ADF&G. However, sometimes a single fishing period would result in fish being delivered on multiple days; this occurred on 95 out of 750 and 57 out of 878, 13% and 6%, of the days with drift

effort for Egegik and Togiak, respectively. Two possible scenarios resulting in multiple delivery dates for a single date fished were: i) vessels from separate delivery dates were separate drift gillnet vessels or ii) the vessels from the later delivery dates were vessels that delivered fish more than once per date fished. These two situations were not distinguishable from ADF&G records.

Thus, a set of criteria was developed to estimate the total number of participating drift vessels when fish caught in one day were delivered over multiple delivery dates. The criteria were: i) the estimated effort must be less than the number of boats registered to fish; registration was required from late June to late July, ii) it must be greater than or equal to the number of boats on each delivery date, iii) it is a combination of the number of unique vessels from each delivery date and iv) the number should be as close as possible to a linear interpolation between the observed efforts from previous and later days. In most cases, one delivery date had a significantly higher number of vessels than the others. Usually, either the delivery date with the highest number of drift vessels or the sum of drift vessels on all delivery dates fit the criteria and was used.

An example of these criteria was the July 5th, 1996 fishing period in Egegik; 132 unique drift vessels delivered on July 5th and 52 unique vessels delivered on July 6th. The largest single value, 132, and the sum, 184, were both less than the 703 vessels registered that day, so both numbers fit criterion two. As the effort on July 4th was 127 and the effort on July 6th was 275, the sum of 184 was chosen because it was closer to a linear interpolation between those two efforts than the largest

single value of 132. The only dates where neither the largest value nor the sum fit the criteria were July 31-August 2, 1989 for the Togiak district and June 25, 1997 for the Egegik district. For the Togiak cases, the largest range of effort between the delivery date with the highest number of vessels and the sum over all delivery dates was 24 vessels. Since there was no effort data for previous dates and no drift vessel registration data, a middle number was chosen. In the sole Egegik case, 551 unique drift vessels delivered fish on June 25th and 246 unique drift vessels delivered fish on June 26th. As the effort was 622 on June 24th and 755 on June 26th, the largest single value of 551 did not seem appropriate. But since the summed total of 797 was higher than the 743 drift vessels registered on June 25th, 90% of the number of vessels registered was chosen.

Set gillnet effort was calculated as the number of set gillnet permits that fished each day. The daily set gillnet effort was equal to the number of unique permits recorded by ADF&G when there was one delivery date per date fished. On days with multiple delivery dates, the set gillnet effort was the sum of the number of unique permits across delivery dates, since it is unlikely that set gillnets would deliver more than once on a given opening.

Daily escapement estimates (data from Tim Baker, ADF&G, Anchorage) were recorded by ADF&G as tower counts upriver from the fishery; every hour fish were counted from a tower for ten minutes per side of the river and counts were then expanded for the entire hour. The number of days spent migrating from the fishing grounds to the tower was assumed to be constant and estimated as two days for the



Egegik River (ADF&G estimate from Flynn et al. 2006) and nine days for the Togiak River (Brannian 1982). The average number of days spent pooling on the fishing grounds was estimated to be 3.6 days for the Egegik fishery. Pooling time is thought to decrease throughout the season (Verhoeven and Davidoff 1962; Flynn et al. 2006). We initially used an average pooling time of 2 days for the Togiak fishery (Brannian 1982), but because decreasing the pooling time resulted in a better model fit, the pooling time we used for the Togiak run reconstruction was 1.5 days (see Results). A sensitivity analysis was run with both pooling time and migration time varied by plus or minus one day. We also investigated replacing the fixed duration of the migration from the fishing district to the counting tower with a normally distributed upriver migration time with the same mean and a standard deviation of three quarters of a day.

#### *Relationship Between Effort and Harvest Fraction*

In preliminary analysis, we compared multiple equations to determine the most appropriate form of the relationship between fishing effort and the harvested fraction of fish pooling in the fishing district, e.g., we compared  $1 - e^{-qE}$ ,  $bE^q$ ,  $b \log_e(E)$ , and for set gillnets only, constant harvest fraction. In the equations,  $E$  was effort and  $b$  and  $q$  were constants. Effort was either the number of drift gillnet vessels (or set gillnet permits) or the number of vessels (or set gillnets) multiplied by the length of the fishing opening. The drift and set gillnetters used the same fishing area, but the drift fleet occupied the section of the area that fish arrive at first; therefore, both models with the drift and set gillnetters fishing together (e.g.,

Table 1.1, Equation 3) or with a sequential harvest were explored (e.g., Table 1.1, Eq. 2). The drift fleet tended to catch a much larger proportion of the fish than the set gillnetters, so models conditional on whether the drift fleet was fishing were explored (e.g., Table 1.1, Eq. 1). Set gillnet effort was thought to vary less than the drift effort, so models with the set gillnetters harvesting a constant fraction of the fish, independent of drift gillnet effort, were explored (e.g., Table 1.1, Eq. 4). In 1997 the Alaska Board of Fisheries changed management of the Egegik district to allocate 14% of the catch to set gillnet gear, whereas previously there was no allocation goal; therefore, Egegik models with a constant efficiency parameter,  $b$ , (e.g., Table 1.1, Eq. 5) or with one efficiency parameter for years before 1997 and one for years after 1996 (e.g., Table 1.1, Eq. 1) were explored (State of Alaska 2010, provision 5AAC 06.365).

To select the form of the effort model, the predicted harvest fraction from each equation was compared to a rough harvest fraction. The rough harvest fraction was calculated as

$$(1.1) \quad \tilde{f}_i = \frac{C_i}{C_i + T_{i+m+j}}$$

$\tilde{f}_i$  = the rough harvest fraction on day  $i$ ;

$C_i$  = the sum of the drift gillnet and set gillnet catches;

$T_{i+m+j}$  = the observed tower count on day  $i+m+j$ ;

$m$  = the time spent pooling on the fishing grounds;

$j$  = the migration time from the fishery to the tower.

The best estimates of  $b$  and  $q$  were calculated by minimizing the simple sum of squares of the difference in the predicted harvest fraction and the rough harvest fraction. These best estimates were only used to calculate the best form of the relationship between effort and harvest fraction. The values of the parameters were estimated during the run reconstruction. In preliminary analysis, the number of vessels (or permits) outperformed the number of vessels multiplied by the length of the fishing opening; therefore, the number of vessels multiplied by the length of the fishing opening was not used as a measure of effort.

The competing equations were compared using the Akaike Information Criteria (AIC); eight years of data spread throughout the 25 years of available data was used. The eight years of data for Togiak all showed similar results. An additional five years were used for Egegik because the earlier years showed one result and the later years showed a different result, so all middle years were included to find the best year to switch between equations. The resultant daily harvest rate equation

chosen for the run reconstruction (Tables 1.1 and 1.2) (see Results) assumed a sequential harvest, where the drift gillnet fleet harvested first and the set gillnet fleet harvested from the remaining fraction. The daily harvest rate was calculated as

$$(1.2) \quad \hat{f}_i = \hat{b}_y \left( 1 - e^{-\hat{q}_d E_{i,d}} \right) + \left[ 1 - \hat{b}_y \left( 1 - e^{-\hat{q}_d E_{i,d}} \right) \right] \left( 1 - e^{-\hat{q}_s E_{i,s}} \right)$$

$\hat{f}_i$  = the daily harvest fraction for day  $i$ ;

$\hat{b}_y$  = a drift fleet efficiency parameter (with Egegik having a separate efficiency parameter for years 1996 and earlier,  $\hat{b}_{96}$ , and for years 1997 and later,  $\hat{b}_{97}$ );

$\hat{q}_d$  = the catchability coefficient for the drift gillnet fleet;

$\hat{q}_s$  = the catchability coefficient for set gillnet gear;

$E_{i,d}$  = the estimated number of drift gillnet vessels that fished on day  $i$ ;

$E_{i,s}$  = the number of set gillnet permits that fished on day  $i$ .

### *Run Reconstructions*

The run reconstruction methods, adapted from Starr and Hilborn (1988) and Flynn et al. (2006), used a maximum likelihood approach. All fish arriving on a given day were treated as a single unit (cohort) that was separate from fish arriving on other days; we used a daily run reconstruction because daily to weekly run reconstructions have been shown to be more reliable than annual reconstructions (Starr and Hilborn 1988). Each cohort of arrivals was added to the fishing pool. Since fish tend to pool before entering the spawning ground, there can be multiple

cohorts of fish in the fishing area at any given time. The total number of fish available for harvest on a given day  $i$  was calculated as

$$(1.3) \quad \hat{X}_i = \sum_{t=1}^i \hat{N}_t - \sum_{t=1}^{i-1} \hat{C}_t - \sum_{t=1}^{i-1} \hat{S}_t$$

$\hat{N}_t$  = the number of fish arriving on day  $t$ ;

$\hat{C}_t$  = the number of fish caught on day  $t$ ;

$\hat{S}_t$  = the escapement from the fishery on day  $t$ .

The total stock return was the sum of all the catches and escapements (it was assumed that negligible mortality or interception occur during migration upriver).

Daily harvest rates were applied to each cohort until they left the fishing ground, with the assumption that fish from each cohort present had the same probability of being caught. The predicted drift gillnet and set gillnet catches were calculated as

$$(1.4 \text{ and } 1.5) \quad \begin{aligned} \hat{C}_{d,i,y} &= \hat{b}(1 - e^{-\hat{q}_d E_{i,d}}) \hat{X}_i \\ \hat{C}_{s,i,y} &= \left[1 - \hat{b}(1 - e^{-\hat{q}_d E_{i,d}})\right] (1 - e^{-\hat{q}_s E_{i,s}}) \hat{X}_i \end{aligned}$$

Predicted expanded tower counts of escapement were calculated as

$$(1.6) \quad \hat{T}_i = c\hat{S}_{i-j}$$

$\hat{S}_{i-j}$  = the predicted escapement from the fishery on day  $i-j$ ;

$\hat{T}_i$  = the predicted expanded tower count on day  $i$ ;

$j$  = the migration time from fishery to the tower;

$c$  = the proportion of the escaping fish that reach the tower.

All of the fish that escape the fishery in Egegik were assumed to reach the counting tower (i.e.,  $c = 1$ ). The estimate of  $c$  for Togiak was 0.9 because Togiak has an escapement goal of 20,000 fish spawning below the counting tower, which represents approximately 10% of the mean observed tower counts.

The number of days spent pooling in the fishery was not constant, as pooling time is thought to decrease linearly as the run progresses (Verhoeven and Davidoff 1962). When the mean number of days spent pooling was a whole number, the proportion of fish leaving was calculated as

$$(1.7) \quad \hat{P}_{i,t} = \begin{cases} 0 & \text{for } t < k - 1 \\ 0.5 \left( \frac{i - f}{l - f} \right) & \text{for } t = k - 1 \\ 0.5 & \text{for } t = k \\ \text{the remaining fish} & \text{for } t = k + 1 \end{cases}$$

$\hat{P}_{i,t}$  = the proportion of fish that arrive on day  $i$  and escape after spending  $t$  days pooling;

$f$  = the date when 2.5% of the total run of fish has reached the fishery;

$l$  = the date when 97.5% of the total run of fish has reached the fishery;

$k$  = the mean number of days spent pooling.

When the mean number of days spent pooling was not a whole number, a spread of two days was used to allow the average time spent pooling to be a fraction of a day (Flynn et al. 2006). In this case the proportion of fish leaving was calculated as

$$(1.8) \quad \hat{P}_{i,t} = \begin{cases} 0 & \text{for } t < k \\ 2 \left( \frac{i - f}{l - f} \right) (1 - r) & \text{for } t = k \\ \text{the remaining fish} & \text{for } t = k + 1 \end{cases}$$

where the mean number of days spent pooling was broken up into  $k$  being the whole number of days and  $r$  the remainder (i.e., the mean = 3.6 for Egegik, so  $k = 3$  and  $r = 0.6$ ). Days before  $f$  and after  $l$  were considered equivalent to  $f$  and  $l$ , respectively.

Efficiency and catchability parameters and daily arrivals were estimated by minimizing the simple sum of squares (SSQ) of the difference in natural log transformed observed and predicted values for drift fleet catch, set gillnet catch, and escapement, with an added term included to force the estimated arrival timing to roughly follow a bell-shaped arrival timing; the best estimates of  $b$  and  $q$  from the effort model selection process were used as starting values.



$$\begin{aligned}
 SSQ_{Total} = & \sum_{i,y} \left[ \log_e(Cd_{i,y}) - \log_e(\hat{C}d_{i,y}) \right]^2 + \sum_{i,y} \left[ \log_e(Cs_{i,y}) - \log_e(\hat{C}s_{i,y}) \right]^2 \\
 & + \sum_{i,y} \left[ \log_e(T_{i,y}) - \log_e(\hat{T}_{i,y}) \right]^2 + w_a \sum_{i,y} \left[ \log_e(\hat{N}_{i,y}) - \log_e(\hat{N}_y \phi_{i,y}) \right]^2
 \end{aligned}
 \tag{1.9}$$

$Cd_{i,y}$  = the observed drift gillnet catch;

$\hat{C}d_{i,y}$  = the predicted drift gillnet catch;

$Cs_{i,y}$  = the observed set gillnet catch;

$\hat{C}s_{i,y}$  = the predicted set gillnet catch;

$T_{i,y}$  = the observed escapement;

$\hat{T}_{i,y}$  = the predicted escapement;

$\hat{N}_{i,y}$  = the predicted arrival on day  $i$  of year  $y$ ;

$\phi_{i,y}$  = the daily arrival fraction (a normal distribution rescaled to sum to one) with a mean arrival date of  $\mu_y$  for year  $y$  and a year-invariant standard deviation of  $\sigma$ ;

$\hat{N}_y$  = the estimated total return for year  $y$  (constrained to be greater than or equal to the sum of the catches and escapement for year  $y$ );

$w_a$  = the weight of the arrival timing SSQ (equal to 0.01).

Note:  $\mu_y$  and  $\sigma$  were estimated parameters. A small weight on the arrival timing ( $w_a$ ) was used because although fish arrival was assumed to roughly follow a normal

distribution, the data suggested there often were strong and weak pulses of arriving fish that did not lie on that curve. Fish arrive before and after the tower count data, so predicted escapement values did not contribute to the total SSQ on days with no recorded escapement. Because there were unrealistically high estimated escapements toward the end of the run for Egegik, the arrival timing weight was increased to 0.1 when there was no recorded escapement five days later (see Results). Parameters and daily arrivals for 41 days for Egegik, June 12th to July 22nd, and 53 days for Togiak, June 20th to August 11th, were estimated for the 25 years of data, 1986-2010. To estimate the large number of parameters, a two-step iterative approach was used (Appendix 1.A). Univariate confidence intervals were estimated for the parameters. As a measure of fit to component data sets, we compared the percent reduction in SSQ of the run reconstruction model compared to a null model with each data series fit with its mean value (similar to  $R^2$ ).

#### *Management Strategy Comparison*

Management strategies were compared by calculating, over all years, the means and CVs of the annual catch and escapement, the frequency of escapement below the ADF&G goal range, and the cohort harvest rate throughout the run. The cohort harvest rate was the percentage of fish that arrived on a particular day that were caught while pooling in the fishing district; the run reconstruction model estimated the daily arrivals.

## Results

### *Relationship Between Effort and Harvest Fraction*

In the preliminary analysis, all of the best models used  $1 - e^{-qE}$  as the relationship between harvest fraction and drift effort; the best models for set gillnet effort used either the same relationship as drift effort (Tables 1.1 and 1.2, Eq. 1-3, 5-6, 8-14) or a constant harvest fraction independent of set gillnet effort (Table 1.1, Eq. 4 and 7). In all cases models using the number of drift gillnet vessels or set gillnet permits as the index of effort outperformed those where the number of vessels or permits were multiplied by the length of the fishing opening, so these variables were used for drift gillnet and set gillnet effort.

The model with the lowest AIC score for Egegik (Table 1.1, Eq. 1) had two equations; one equation when only the set gillnet gear was fishing and one when both gears were fishing which did not take set gillnet gear into account (Table 1.1). The second best model (Table 1.1, Eq. 2) was a sequential harvest model, where the drift gillnet fleet harvested first and the set gillnet gear caught a fraction of the remaining fish. This model is more biologically plausible since Egegik and Togiak are terminal fisheries, where fish entering the fishing districts must pass through the drift gillnet fleet fishing area before reaching the set gillnet sites. Equation 1 had a worse fit than Equation 2, but a lower AIC score because it had one less parameter; Equation 1 initially had five parameters, but the constant  $q_s$  in the equation when the drift fleet was fishing was estimated as zero and was removed from the model (Table 1.1). There was only weak evidence for a difference between Equations 1 and

2, since the difference in AIC scores was about two (Table 1.1) (Burnham and Anderson 1998). Accordingly, we used Equation 2 for the run reconstruction (Table 1.1). All other models had a much higher AIC score.

The model with the lowest AIC score for Togiak (Table 1.2, Eq. 10) was similar to the chosen model for Egegik, except that it did not have a drift fleet efficiency parameter; this model had a slightly worse fit, but a better AIC score due to one less parameter (Table 1.2). Since it is unclear whether the Togiak drift fleet could harvest 100% of the fish with enough vessels and to stay consistent with the Egegik model, the model with the efficiency parameter included (Table 1.2, Eq. 11) was chosen for the run reconstruction. The difference in AIC scores between Equations 10 and 11 was less than two (Table 1.2).

#### *Run Reconstructions*

The run reconstructions were able to match the historical data fairly closely (Figures 1.2 and 1.3). We show fits of the model to 2001 data for Egegik and Togiak (Figures 1.2 and 1.3). Fits of the other 24 years (fits were done for years 1986-2010) were similar to those shown in Figures 1.2 and 1.3. Across all years, the reduction in total SSQ for drift gillnet catch, set gillnet catch, and escapement for Egegik was 93%, 87%, and 85%, respectively (in 2001 they were 92%, 87%, and 81%, respectively). The reductions in total SSQ for Togiak were 93%, 93%, and 83%, respectively (in 2001 they were 94%, 91%, and 70%, respectively).

The run reconstruction results were consistent with the model's assumptions about the fisheries. Sockeye salmon arrivals to the fishing districts

loosely conformed to a normal distribution with strong and weak pulses of fish that did not lie on that curve (Figures 1.2a and 1.3a). The Egegik and Togiak run reconstruction models had 89% reduction in total SSQ. The Egegik model fitted drift gillnet catches better than set gillnet catches and escapements, whereas the Togiak model fitted drift gillnet catches and set gillnet catches better.

The estimated Egegik run was generally larger, earlier, more condensed temporally, and more variable than the Togiak run (Table 1.3). The average yearly run size for Egegik was much larger than Togiak, with a higher CV as well. The average yearly mean date of arrival of the Egegik run was fourteen days earlier than that of Togiak; the standard deviation of the yearly mean date was smaller for Egegik than Togiak. The Egegik run was more compact than Togiak, with an estimated standard deviation of a normal run time of 8.02 days for Egegik and 10.60 days for Togiak.

The Egegik drift fleet was estimated to catch a smaller fraction of the fish than the Togiak fleet at a given effort level (Table 1.4), as the  $\hat{q}_d$  estimate for Togiak was larger than the estimate for Egegik and the  $b$  estimate for Togiak was larger than one of the estimates for Egegik. However, the Egegik drift gillnet fleet tended to have a higher estimated harvest fraction than Togiak (Table 1.5) due to higher drift effort; the mean drift effort for Egegik prior to 1997, Egegik post 1996, and Togiak was 250, 203, and 26, respectively.

Averaged over 25 years, the cohort harvest rate for the Togiak stock was less variable throughout the season than that of the Egegik stock (Figure 1.4). The mean

cohort harvest rate for the Egegik stock ranged from 15% early in the season to 90% during the middle of the run, whereas the Togiak stock ranged from 20% at the end of the run to 70% in the middle of the run. The cohort harvest rate was lower at the beginning and end of the run due to lower effort levels.

The estimated tower counts increased at the end of the run when there was no data to provide an escapement penalty in the likelihood. The actual tower counts ended before the last day of the run reconstructions (on average 3.8 and 5 days prior for Egegik and Togiak, respectively). These escapement estimates were unrealistically high for Egegik, so the arrival penalty ( $w_a$ ) was increased from 0.01 to 0.10 for those cohorts that arrived five days prior to a day with no recorded escapement. This change in arrival penalty, on average, decreased the arrival estimates at the end of the run and increased the arrival estimates in the middle of the run. There was little effect on the total yearly arrivals, an average increase of 0.01%. Even with the increased arrival penalty, the estimated tower counts still increased at the end of the run. However, the tower count estimates were within the range of escapement seen on days when data was available (Figures 1.2d, 1.3d).

The run reconstructions were generally robust to the pooling and migration time assumptions (details in Appendix 1-B). The parameter estimates for the harvest fraction equations were sensitive to the pooling time assumption. When assuming a longer pooling time in the fishery, the  $q$  and  $b$  parameter estimates were lower. However, the cohort harvest rates were not much affected; the longer pooling time and decreased efficiency (or vice versa) resulted in a similar total harvest on

each cohort. Decreasing the pooling time in Togiak from 2 days (Brannian 1982) to 1.5 or 1 day decreased the total SSQ by improving the fit to the escapement data. We chose to use 1.5 days since Brannian (1982) showed a pooling time greater than 1 day. All other changes to the pooling and migration time assumptions increased the total SSQ.

### *Management Strategy Comparison*

The Egegik fishery caught a higher percentage of the returning fish, but the Togiak catch was less variable (Table 1.3, Figures 1.5 and 1.6). Egegik had a larger run than Togiak, so the mean catch was larger; but the CV of catch was higher for Egegik than for Togiak. The Egegik fishery caught 80% of the run on average, 70% by the drift gillnet fleet and 10% by the set gillnetters; the Togiak fishery caught 63% of the run on average, 36% by the drift gillnet fleet and 27% by the set gillnetters.

Escapement to the Egegik River was closer to the upper end of its escapement goal range and slightly less variable than that of Togiak (Table 1.3). The mean escapement to the Egegik River was 1.4 million, the upper end of the 800,000-1,400,000 escapement goal range. The mean escapement to the Togiak River was 202,000, which is closer to the middle of the 100,000-250,000 escapement goal range. The Togiak escapement was below the escapement goal range once in the 25 years and above eight times; the Egegik escapement was never below the escapement goal range and above eleven times.

Total catches, escapements, and the percentage of the run caught in the fishery increased as the run size increased. The total catch was highly correlated with total run size, with correlation coefficients of 0.98 and 0.97 for Egegik and Togiak, respectively. The percentage of the run caught was also correlated with run size, but less correlated than total catch, with correlation coefficients of 0.58 and 0.61 for Egegik and Togiak, respectively. The Egegik fishing district is more actively managed to obtain an escapement goal than the Togiak fishing district; the correlation coefficients between escapement and run size reflected this, with values of 0.85 and 0.43 for Togiak and Egegik, respectively.

## Discussion

The objective of this paper was to compare the performance of two Alaskan fisheries, one managed primarily through emergency order openings and one managed primarily by a fixed fishing schedule. Management by emergency order openings gives a manager more control over the fishery, but a fixed fishing schedule provides a more predictable catch. With management by emergency order, the Egegik fishery met the minimum escapement goal every year and had less variable escapement. At the same time, the Egegik fishery caught a higher percentage of the run than the Togiak fishery. In contrast, the fixed fishing schedule in Togiak resulted in a harvest rate spread more evenly throughout the fishing season and less yearly variation in catch. The main goal of both fisheries was to meet the escapement goal



range. Hence, the variation in escapement for Togiak was similar to that for Egegik, even though escapement in Togiak was highly correlated with run size.

Management by emergency order fits the needs of the Egegik fishery, while a fixed fishing schedule is more suited to the Togiak fishery. Over-harvest would be intrinsically more likely for Egegik than for Togiak because the Egegik fishery has a smaller fishing area and more fishing effort (Table 1.5); the Egegik District is approximately 60 square miles, while the Togiak District is over 150 square miles. Therefore, a more active management strategy is required to ensure the escapement goal is met. Escapement information is updated more rapidly for Egegik than for Togiak, since the migration time from the fishery to the counting tower is shorter for Egegik (2 days) than for Togiak (9 days). More up to date information can increase the performance of management by emergency order. For the less-intensive Togiak fishery, a fixed fishing schedule provides steady harvest and escapement, while requiring less informative data. Less effort combined with a fixed fishing schedule increases the efficiency of the fishing fleet (Link et al. 2003; Hilborn et al. 2005).

#### *Management Strategy Comparison*

Management by emergency order openings provides managers with more control over escapement. The Egegik fishery was never below the escapement goal range, but Togiak was below the goal range once. Emergency order openings allow managers to be more cautious early in the run, thereby increasing the chances of meeting the minimum escapement goal. However, a more cautious approach may

increase the chance of exceeding the escapement range during strong runs; Egegik exceeded the escapement range eleven times, compared to eight for Togiak. However, the Egegik fishery may also be more likely to have an escapement outside of the goal range because the Egegik run is more variable and compressed than the Togiak run.

A fixed fishing schedule provides a more stable harvest rate. The consistent off days in a fixed fishing schedule allows the harvest to be spread more evenly throughout the run. Togiak had a more sustained harvest rate throughout the season, although both fisheries tended to underharvest the tails of the run. One benefit of a stable harvest rate, similar to a fixed harvest rate policy, is an increase in the profitability of the fishery (Steiner et al. 2011). In addition, different stocks and substocks may have different arrival timings, so a more spread out harvest would better protect all of them (Hendry and Day 2005). The Egegik and Togiak stocks of salmon returning to a single river are separated into substocks by arrival timing and spawning location (Habicht et al. 2007; Dann et al. 2009). Since males arrive earlier than females, more fishing pressure late in the season could result in more females being caught than males (Morbey 2000). Thus, another benefit of a stable harvest rate is that the sex ratio would be better protected.

The effects of a management strategy vary depending on the dynamics of the fishery and the fishing district. The Egegik fishery harvested a higher percentage of the run on average than the Togiak fishery, even though the Egegik run was larger. The Egegik fishery had more fishing effort and a smaller fishing area, so the overall

harvest rate was higher, even if the efficiency was lower for each individual drift vessel or set gillnet permit.

Management by emergency order versus a fixed fishing schedule lead to different socioeconomic outcomes. The Egegik fishery is designed to maximize catch. Drift vessels from other fishing districts in Bristol Bay, except Togiak, can switch to Egegik between June 25-July 17 with only a 48-hour penalty of not fishing and no penalty outside of those dates (State of Alaska 2010, provision 5 AAC 06.370). Since fisherman in other districts can switch to Egegik during strong runs and switch out of Egegik during weak runs, fishermen seeking high profits are more attracted to Egegik than Togiak. The Togiak District began exclusivity in 1996, where drift vessels that register for the Togiak fishing district cannot fish in any other fishing districts and vessels that register for other districts cannot switch to the Togiak district from June 1-July 27 (State of Alaska 2010, provision 5 AAC 06.370). Because Togiak has more constant fishing openings and fishermen cannot leave the district during weak runs, fishermen looking for more predictability and less competition are more attracted to Togiak than Egegik. The contrasting goals of the Egegik and Togiak fishermen require different management strategies; Egegik requires more active management than Togiak to ensure the escapement goal is met, whereas Togiak requires exclusivity to allow livelihood fishermen to be competitive.

### *Run Reconstructions*

The run reconstruction model we used has seven major assumptions i) fish pool in the fishing district and the duration of pooling decreases throughout the run, ii) all fish caught in the fishing districts are returning to the fishing district, iii) all fish are equally vulnerable to catch, iv) fish arriving on the same day stay together as a cohort, v) there is a fixed migration time from escaping the fishery to being counted by the tower, vi) there is no mortality or interception during the migration, and vii) the catch and escapement counts are accurate.

The run reconstructions are robust to the model assumptions (details in Appendix 1-B). The sensitivity analyses showed that changes to the pooling and migration time assumptions resulted in worse model fits, although the arrival and harvest fraction estimates were relatively insensitive to such changes. Sensitivity analyses showed the run reconstruction was robust to assumptions i, iv, and v. The Egegik and Togiak fisheries did catch some fish that belong to other stocks from 2006-2008 (Dann et al. 2009); thus the run reconstruction may overestimate the amount of fish returning to those systems if those years are typical of all years of the run reconstruction. However, including the fish straying from other locations into the fisheries will provide a more realistic comparison of the performance of management strategies. Slight variations in vulnerability should have a similar effect to differing pooling times. Therefore, the equal vulnerability assumption was met because the model was fairly robust to different pooling times. Subsistence and sport catch of sockeye salmon in Bristol Bay is negligible compared to the large

commercial fishery, therefore interceptions during migration are considered insignificant. Both catch and tower count data have been shown to be quite accurate (Anderson 2000).

The run reconstruction and resulting management strategy comparison are limited by the data available. The tower counts of salmon escapement had gaps at the beginning and end of the runs. We were somewhat limited by the accuracy of the approximations used to estimate drift effort, particularly in using the number of deliveries to estimate relative levels of effort. It is possible the behavior of the fishing fleet in Togiak may have differed somewhat prior to the implementation of exclusivity in 1996. Despite these caveats, we feel that our reconstructed abundances are reasonable, and sufficient for the purpose of comparing the results of the two management strategies.

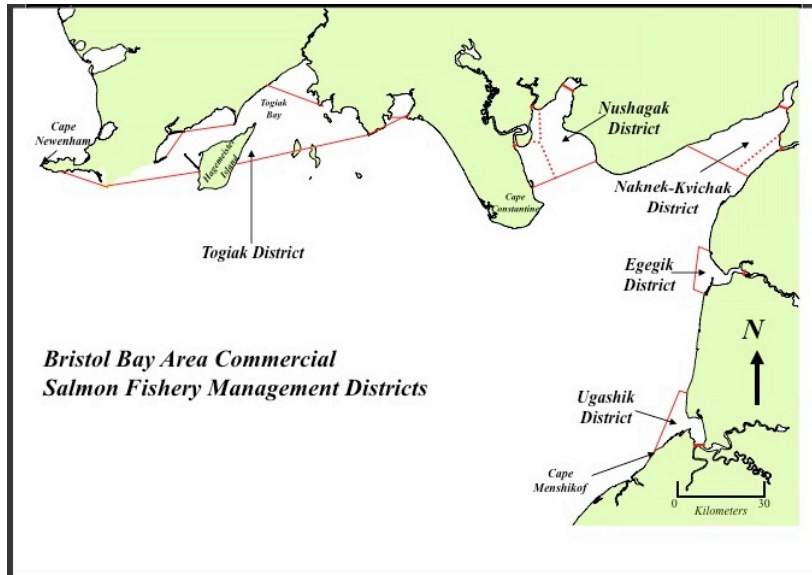
This paper shows that both management by emergency order openings and a fixed fishing schedule can be successful. Benefits of management by emergency order openings are a higher mean catch and more control over escapement; however, this management is more expensive and requires more up to date information. Benefits of a fixed fishing schedule are less yearly variation in catch and a harvest spread more evenly throughout the season; however, overharvest is more likely. Management by emergency order openings is an appropriate choice for the Egegik fishery because the goal of the Egegik fishery is to maximize harvest while meeting the escapement goal. A fixed fishing schedule is an appropriate choice

for the Togiak fishery because it increases efficiency, while the exclusivity policy keeps effort more constant and reduces the likelihood of over-fishing.

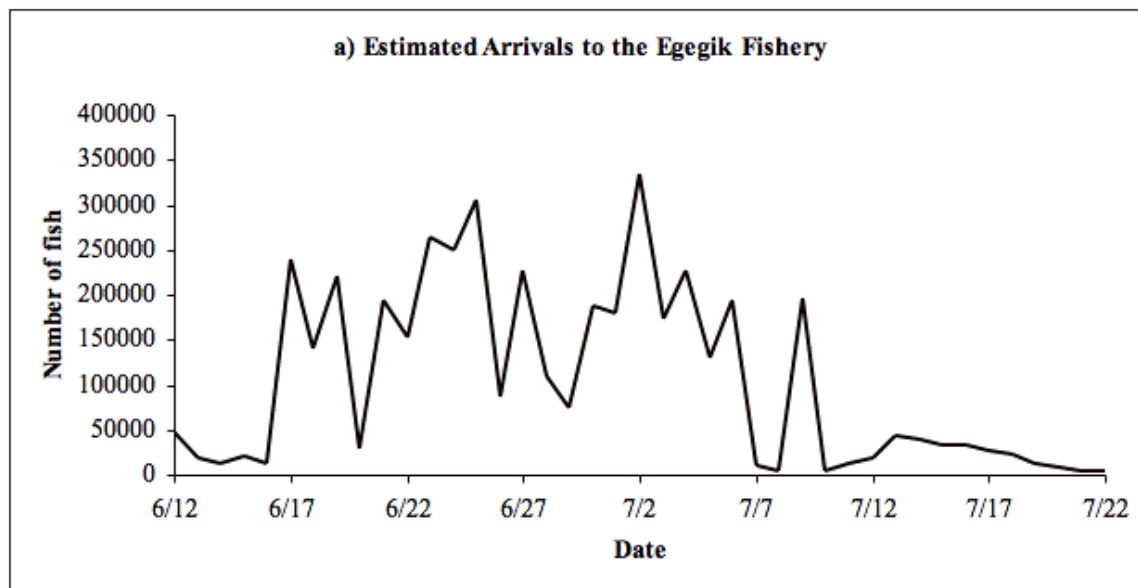
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## Figures



**Figure 1.1. Bristol Bay Map.** Map of Bristol Bay commercial fishing districts. Produced by ADF&G.



**Figure 1.2. Egegik Run Reconstruction Results.** (a) Estimated arrivals, observed and predicted (b) drift gillnet catch, (c) set gillnet catch, and (d) tower counts for the Egegik fishery in 2001. The Egegik model fitted drift gillnet catches better than set gillnet catches and escapements.

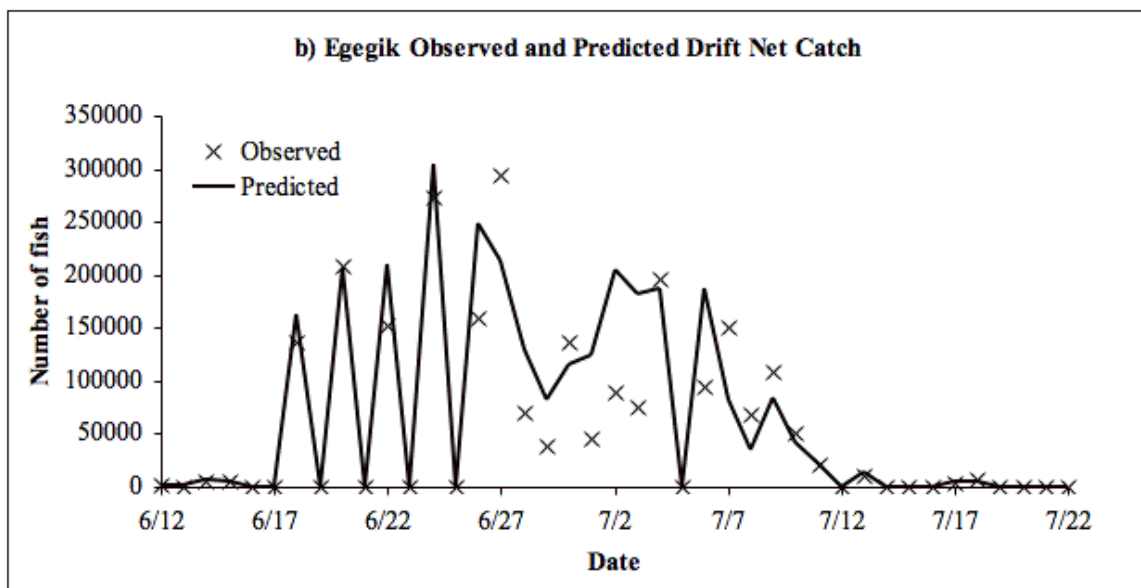


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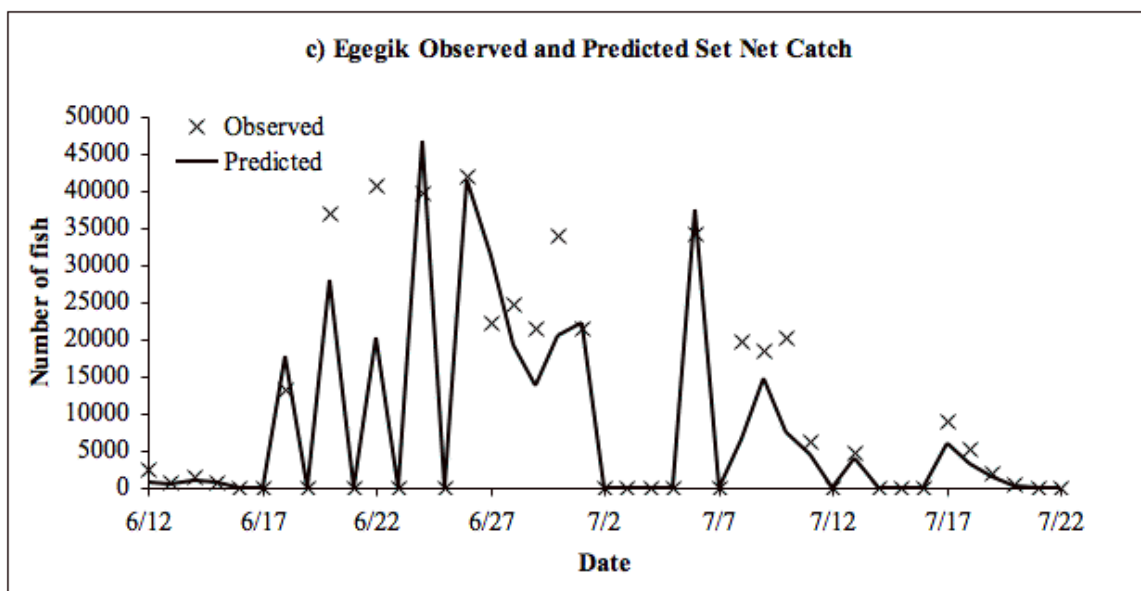


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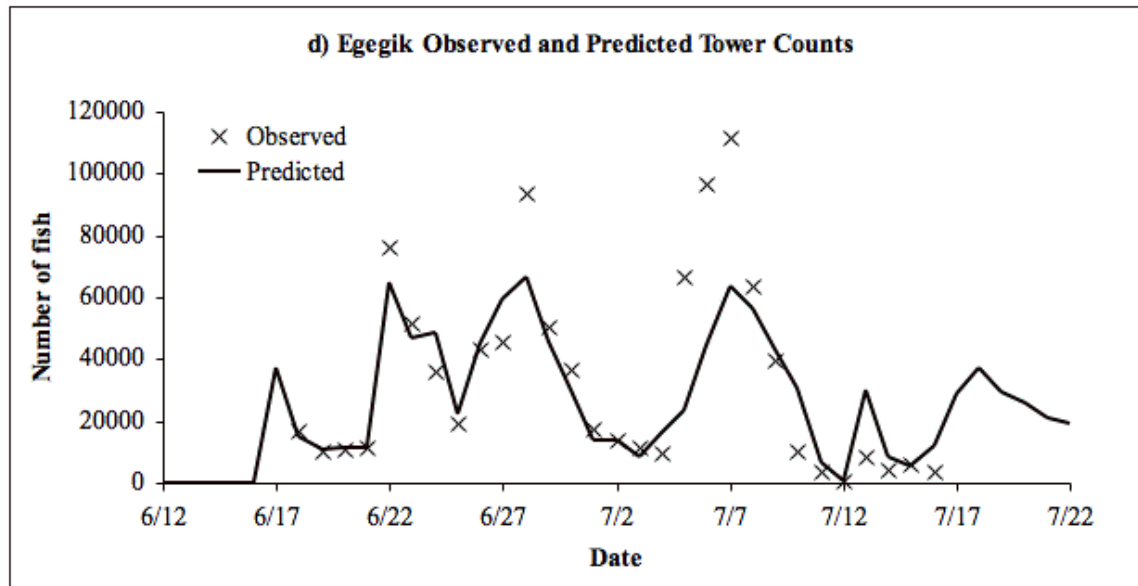
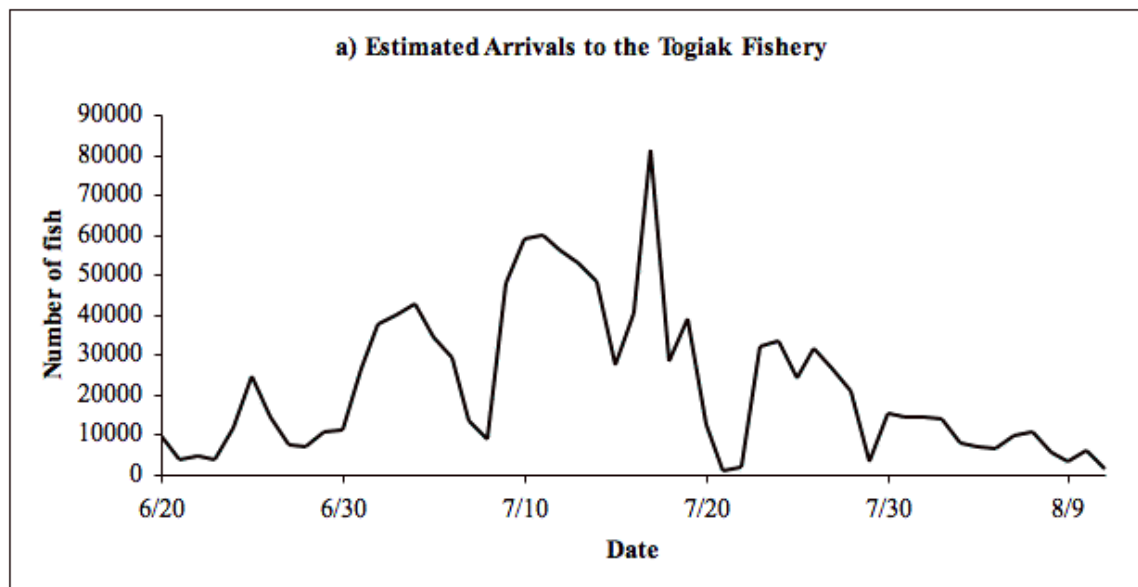


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**Figure 1.3. Togiak Run Reconstruction Results.** (a) Estimated arrivals, observed and predicted (b) drift gillnet catch, (c) set gillnet catch, and (d) tower counts for the Togiak fishery in 2001. The Togiak model fitted set gillnet catches better than drift gillnet catches and escapements.

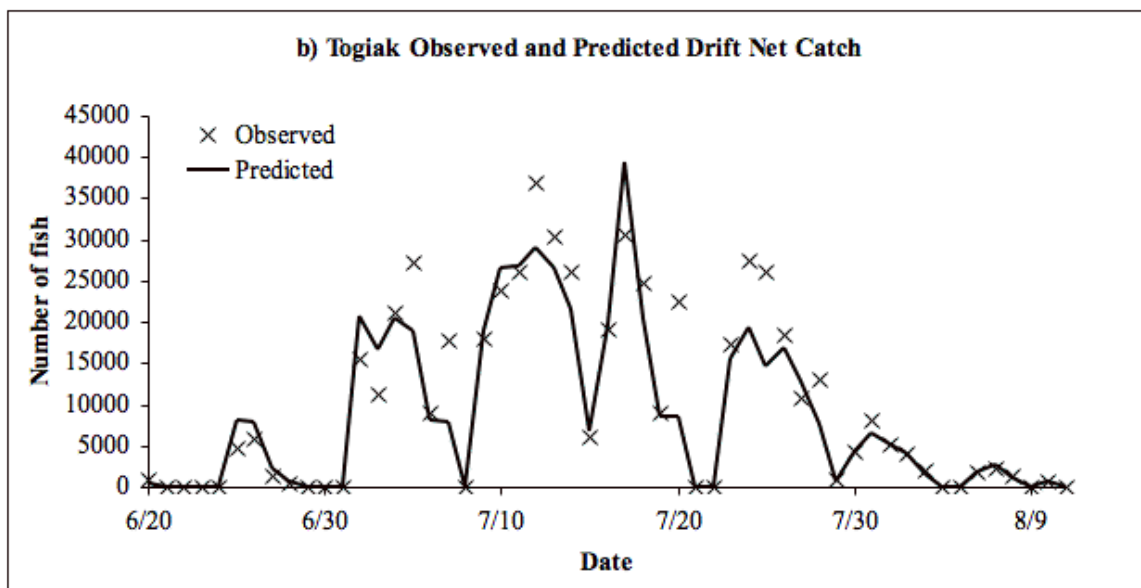


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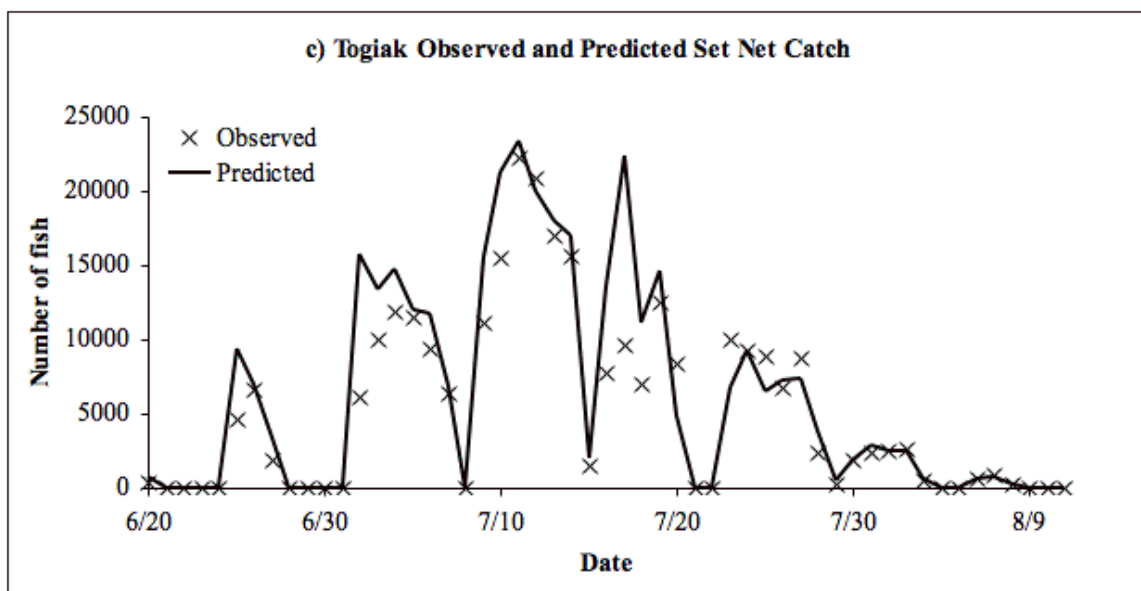


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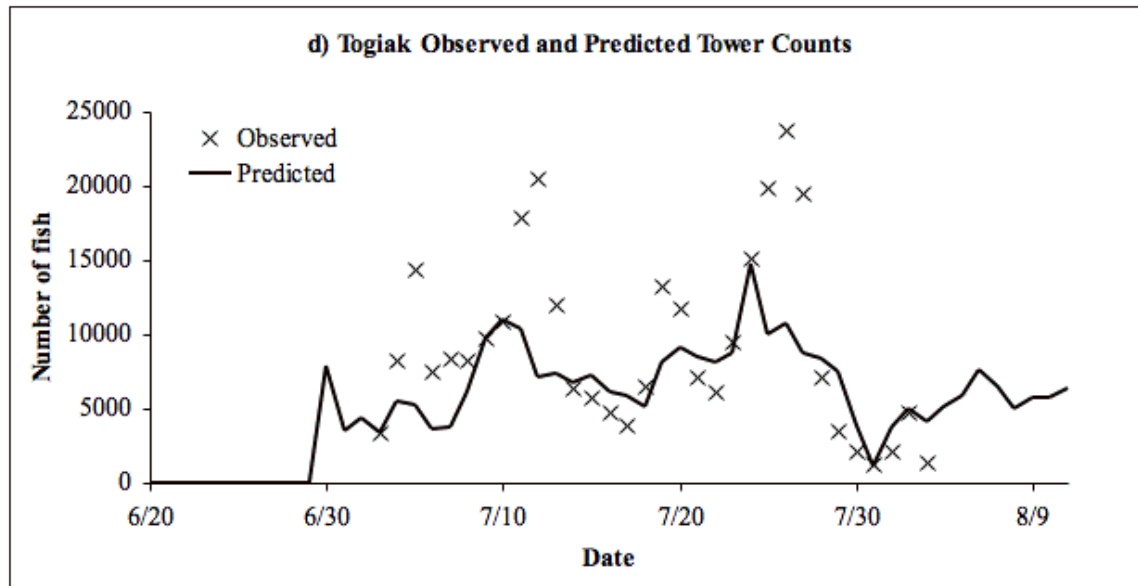
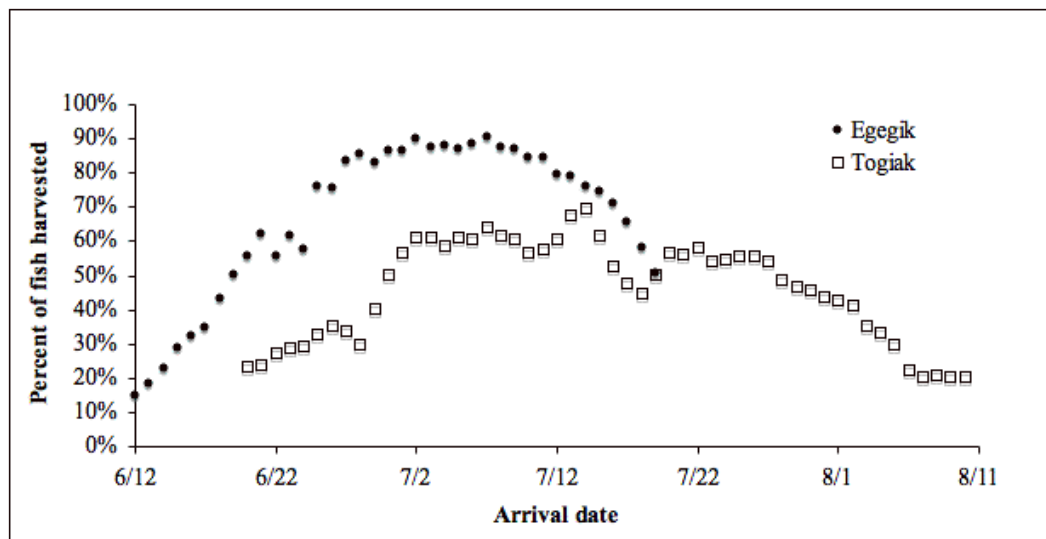
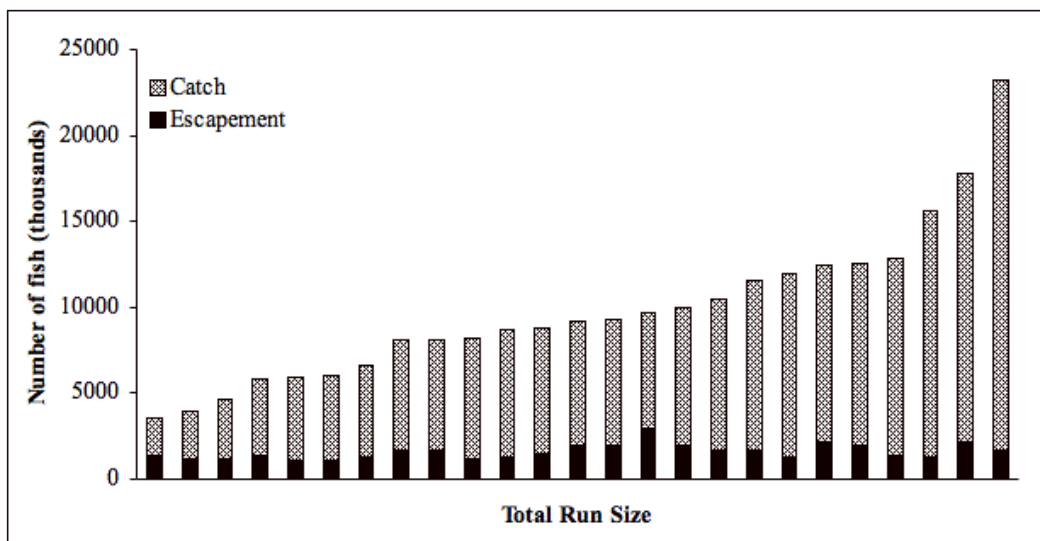


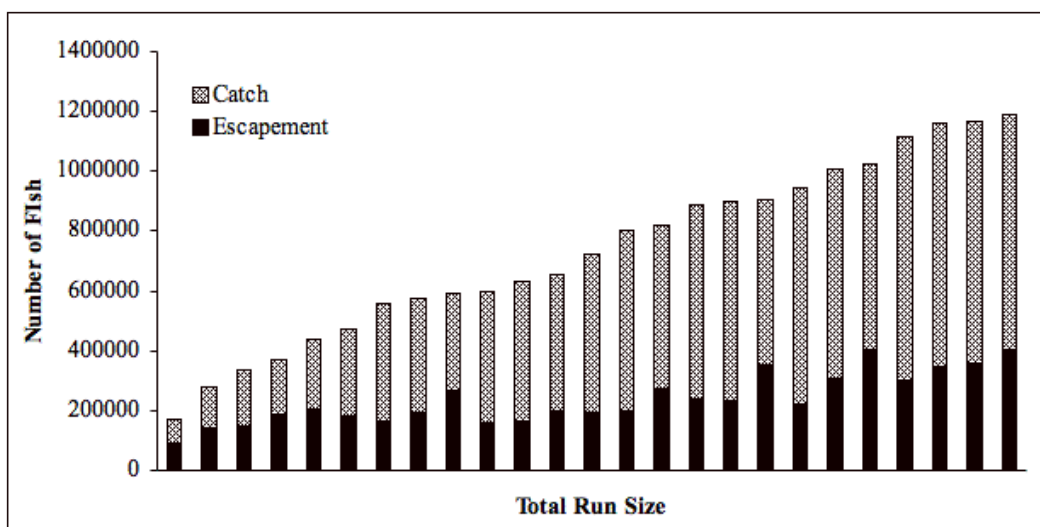
Figure 1.3. continued...



**Figure 1.4. Historical Mean Cohort Harvest Rate.** Mean cohort harvest rate by date from 1986-2010 for the Egegik and Togiak fisheries. The cohort harvest rate for the Togiak stock was less variable throughout the season than that of the Egegik stock.



**Figure 1.5. Egegik Historical Catch and Escapement vs. Run Size.** Observed catch and expanded escapement by total run size for Egegik from 1986-2010. Expanded escapement is the observed escapement plus the estimated escapement on days when there was no escapement data. On average the Egegik fishery caught a higher percentage of the run than the Togiak, even though the mean run size was higher.



**Figure 1.6. Togiak Historical Catch and Escapement vs. Run Size.** Observed catch and expanded escapement by total run size for Togiak from 1986-2010. See note on expanded escapement in Figure 1.5 caption. The mean run size and catch of Togiak was less variable than those of Egegik.

## Tables

**Table 1.1. Egegik Effort to Harvest Fraction Relationships.** Harvest fraction equations based on drift gillnet and set gillnet fishing effort ( $E_d$  and  $E_s$ , respectively) for the Egegik district with corresponding AIC and  $\Delta$  AIC values. Drift and set catchability parameters are indicated by  $\hat{q}_d$  and  $\hat{q}_s$ , respectively. Efficiency parameters are indicated by  $\hat{b}$ . A  $y$  script indicates two parameters, one for years 1996 and earlier and one for 1997 and later. Equation 2 is the most plausible biologically because fish entering the fishing district must pass through the drift gillnet fleet fishing area before reaching the set gillnet sites.

	Harvest fraction equation (Egegik)	p	AIC	$\Delta$ AIC
	$\hat{b}_y(1 - e^{-\hat{q}_d E_d})$ , if drift fleet fishes			
1	$1 - e^{-\hat{q}_s E_s}$ , if drift fleet does not fish	4	7312.45	-
2	$\hat{b}_y(1 - e^{-\hat{q}_d E_d}) + [1 - \hat{b}_y(1 - e^{-\hat{q}_d E_d})](1 - e^{-\hat{q}_s E_s})$	4	7314.49	2.04
3	$\hat{b}_y(1 - e^{-(\hat{q}_d E_d + \hat{q}_s E_s)})$	4	7317.75	5.31
4	$\hat{b}_y(1 - e^{-(\hat{q}_d E_d + \hat{q}_s)})$	4	7319.83	7.38
5	$\hat{b}(1 - e^{-(\hat{q}_{d(y)} E_d + \hat{q}_{s(y)} E_s)})$	5	7324.96	12.51
6	$\hat{b}(1 - e^{-(\hat{q}_{d(y)} E_d + \hat{q}_s E_s)})$	4	7338.32	25.87
7	$\hat{b}(1 - e^{-(\hat{q}_{d(y)} E_d + \hat{q}_s)})$	4	7342.82	30.37
8	$\hat{b}(1 - e^{-\hat{q}_d E_d}) + [1 - \hat{b}(1 - e^{-\hat{q}_d E_d})](1 - e^{-\hat{q}_s E_s})$	3	7345.12	32.68
	$\hat{b}(1 - e^{-\hat{q}_d E_d})$ , if drift fleet fishes			
9	$1 - e^{-\hat{q}_s E_s}$ , if drift fleet does not fish	3	7357.39	44.94

**Table 1.2. Togiak Effort to Harvest Fraction Relationships.** Harvest fraction equations based on drift gillnet and set gillnet fishing effort ( $E_d$  and  $E_s$ , respectively) for the Togiak district with corresponding AIC and  $\Delta$  AIC values. Drift and set catchability parameters are indicated by  $\hat{q}_d$  and  $\hat{q}_s$ , respectively. Efficiency parameters are indicated by  $\hat{b}$ . Equations 10 and 11 had similar AIC scores, but Equation 11 was used for the run reconstruction to stay consistent with the equation used for Egegik.

	Harvest fraction equation (Togiak)	p	AIC	$\Delta$ AIC
10	$(1 - e^{-\hat{q}_d E_d}) + [1 - (1 - e^{-\hat{q}_d E_d})](1 - e^{-\hat{q}_s E_s})$	2	3776.93	-
11	$\hat{b}(1 - e^{-\hat{q}_d E_d}) + [1 - \hat{b}(1 - e^{-\hat{q}_d E_d})](1 - e^{-\hat{q}_s E_s})$	3	3778.73	1.80
12	$1 - e^{-(\hat{q}_d E_d + \hat{q}_s E_s)}$	2	3780.80	3.87
13	$\hat{b}(1 - e^{-\hat{q}_d E_d}) + (1 - e^{-\hat{q}_s E_s})$	3	3783.53	6.59
14	$(1 - e^{-\hat{q}_d E_d}) + (1 - e^{-\hat{q}_s E_s})$	2	3795.27	18.34

**Table 1.3. Attributes of the Egegik and Togiak Runs and Fisheries.** Estimates of run size, run timing, and percent of the run caught and the observed catch and escapement for the Egegik and Togiak fisheries, with CVs. The Egegik fishery caught a higher percentage of the run even though the mean size was larger and more condensed temporally. However, the Togiak catch was less variable.

	Egegik	Togiak
Mean run size	9,921,699	764,304
CV run size	0.44	0.39
Mean run date	July 3rd	July 17th
SD mean run date	2.23 days	3.73 days
Mean catch	8,205,451	495,776
CV catch	0.52	0.45
Percent catch by drift		
gillnet	70%	36%
Percent catch by set		
gillnet	10%	27%
Mean escapement	1,412,116	202,496
CV escapement	0.31	0.33
SD run time	8.02	10.60

**Table 1.4. Egegik and Togiak Run Reconstruction Parameter Estimates.** Drift gillnet efficiency ( $\hat{b}_{96}$ ,  $\hat{b}_{97}$ , and  $\hat{b}$ ), drift gillnet catchability ( $\hat{q}_d$ ), and set gillnet catchability ( $\hat{q}_s$ ) estimates for the Egegik and Togiak fishing fleets with 90% confidence intervals.

Parameter	Estimate	Upper CI	Lower CI
<b>Egegik</b>			
$\hat{b}_{96}$	0.56	0.57	0.55
$\hat{b}_{97}$	0.48	0.49	0.47
$\hat{q}_d$	0.0059	0.0062	0.0057
$\hat{q}_s$	0.00088	0.00092	0.00085
<b>Togiak</b>			
$\hat{b}$	0.55	0.56	0.54
$\hat{q}_d$	0.0199	0.0206	0.0193
$\hat{q}_s$	0.0088	0.0090	0.0085

**Table 1.5. Percentage of Effort with Estimated Harvest Fraction.** The percentage of the drift gillnet effort corresponding to a range of estimated harvest fractions for Egegik prior to 1997, Egegik post 1996, and Togiak. The Egegik drift gillnet fleet tended to have a higher estimated harvest fraction than Togiak due to higher drift effort.

Estimated harvest fraction	Egegik before 1997	Egegik after 1996	Togiak
0	0.26	0.27	0.34
0.01-0.10	0.05	0.09	0.06
0.11-0.20	0.04	0.07	0.13
0.21-0.30	0.07	0.07	0.20
0.31-0.40	0.09	0.19	0.20
0.41-0.50	0.19	0.31	0.07
>0.50	0.29	NA	0.01



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## Appendix 1.A

To estimate the large number of parameters, a two-step iterative approach was used with two or more starting values. There are over 1,000 parameters to estimate for each system, but few parameters affect the SSQ for all years; the harvest fraction equation parameters and the standard deviation of run timing affect all years of data, but the yearly mean date of run timing and the daily arrival estimates affect one year. The first step of the iterative approach is to estimate the mean date of run timing and the daily arrival estimates for each year separately. The second step is to estimate the harvest fraction parameters and the standard deviation of run timing. Iterations, steps one and two combined, are run until the difference in the total SSQ is less than one-thousandth of a percent. The Togiak run reconstructions took between six and sixteen iterations to converge, with a median of seven; the Egegik run reconstruction took between nine and thirteen iterations to converge, with a median of ten.

Lower starting values for the parameters required more iterations to converge, but the resulting estimates were not significantly different. Different starting values for the parameters were used on the chosen models. The two lower starting values for Egegik took ten and eleven iterations to converge, but the higher starting values took nine; the lower starting values for Togiak took sixteen iterations, but the higher starting values took seven. All resulting parameter estimates for Egegik and the parameter estimates from step two of the iterative

approach for Togiak were the same regardless of starting values. Eight of the twenty-five yearly mean dates were different for Togiak, but all were within two days. All yearly total run sizes for Togiak were within two percent and all daily arrivals were within 1,070 fish; all six daily arrivals with a difference greater than 500 were in 2006.

## Appendix 1.B

The run reconstruction model we used has seven major assumptions

i) fish pool in the fishing district and the duration of pooling decreases throughout the run, ii) all fish caught in the fishing districts are returning to the fishing district, iii) all fish are equally vulnerable to catch, iv) fish arriving on the same day stay together as a cohort, v) there is a fixed migration time from escaping the fishery to being counted by the tower, vi) there is no mortality or interception during the migration, and vii) the catch and escapement counts are accurate.

We first consider fish behavior, i.e., assumption i) fish pool in the fishing district and the duration of pooling decreases throughout the run, iv) fish arriving on the same day stay together as a cohort, and v) there is a fixed migration time from escaping the fishery to being counted by the tower. Verhoeven and Davidoff (1962) showed that sockeye salmon going to the Fraser River arrived at the estuary up to a month before entering the river mouth. It can safely be assumed that sockeye arrive at the Egegik and Togiak estuaries some time before entering the river. Carney and Adkison do not know of any studies on the amount of time spent pooling on the fishing grounds or whether pooling time decreases throughout the run for either fishery.

A sensitivity analysis was run with both pooling time and migration time varied by plus or minus one day, as well as a normal upriver migration time with the same mean migration time and a standard deviation of three quarters of a day. The

run reconstructions are robust to the pooling time and migration time assumptions; Figure 1.B-1 shows the estimated daily arrivals with varied assumptions. Changing the pooling and migration time assumptions for the Egegik fishery resulted in worse fits. Decreasing the upriver migration time by one day resulted in a similar fit, but all other changes resulted in much worse fits. The greatest difference of estimated arrivals between models for the same day is fifteen percent of the total run.

Differences for nineteen of 1,025 days are greater than ten percent, however, the difference in cumulative arrivals is less than five percent of the total run within the next two days. The migration time assumption had little effect on the parameter estimates for the harvest fraction equation. However, the pooling time assumption did have an effect (Table 1.B-1) because the same amount of effort is estimated as more or less efficient depending on how many cohorts of fish are pooling in the fishing district. The fleet efficiency parameters are affected by the pooling time assumption, but the cohort harvest rates are robust; 90% of the 950 cohort harvest rates differ by ten percent or less between 3.6 and 2.6 days pooling and all dates of the average cohort harvest rate for the fishery are within eight percent.

The drift fleet efficiency parameters for the Egegik fishery are lower than expected. The two  $b$  values for Egegik should be closer to one because it is estimated that 300 drift vessels can harvest most of the fish up to 700,000 with a 5-hour opening (Westing et al. 2006). As mentioned previously, an incorrect pooling time assumption would cause lower estimated values; however, if the fishery were open on consecutive days, most of the fish would be harvested. There may not have been



enough days with an actual harvest rate close to one to estimate higher values due to only 35.8% of the days having 300 or more drift vessels, many days with more than 700,000 fish estimated in the fishery, and/or the fishing openings were not long enough to catch all the fish.

Decreasing the pooling time assumption for the Togiak fishery resulted in better fits, but changing the migration time assumptions resulted in worse fits. Pooling times of one or one and half days resulted in better fits than a pooling time of two days; a pooling time of one day had a slightly better fit for arrival timing than a pooling time of one and a half days. The greatest difference of estimated arrivals for one day is ten percent of the total run; twenty days are greater than five percent and, like Egegik, the difference in cumulative arrivals is lowered within two days. The Togiak harvest fraction equation parameter estimates show similar patterns as Egegik; the pooling time assumption has an effect, but migration time assumptions do not (Table 1.B-2).

Regarding assumption ii), that all fish caught in the fishing districts are returning to the fishing district: Dann et al. (2009) showed that from 2006-2008 73%-86% of the fish caught in the Egegik fishery were from the Egegik stock and 74%-97% of the fish caught in the Togiak fishery were from the Togiak stock. Fish from the Egegik stock are caught in other fisheries, especially to the Ugashik and to a lesser extent the Naknek-Kvichak; fish from the Togiak stock are mostly caught to the Nushagak fishery. The Egegik fishery catches fish from the Ugashik and Naknek-

Kvichak, while the Togiak fishery catches fish from the Kuskokwim and sometimes the Nushagak. The actual assumption is that the amount of fish from other stocks intercepted by the Egegik and Togiak fisheries is equal to the amount of fish from the Egegik and Togiak stocks intercepted by other fisheries. From 2006-2008, when genetic samples of the commercial fisheries were taken, fish of Egegik origin represented 22.4% of the total run from Bristol Bay, yet, the Egegik fishing district caught 24.8% of the total fish harvest in Bristol Bay; fish of Togiak origin represented 1.6% of the total run from Bristol Bay, yet, the Togiak fishing district caught 2% of the total fish harvest. The Egegik and Togiak fishing districts intercepted more fish en route to other areas than the number of fish from their stocks intercepted by other fisheries. The average Egegik run from 2006-2008 represented 90% of the total catch and escapement from the Egegik fishery; the average Togiak run from 2006-2008 represented 84% of the total catch and escapement from the Togiak fishery. If catches from 2006-2008 are consistent with all years, both the Egegik and Togiak run reconstructions would overestimate the fish arrivals. The purpose of this project is to compare management strategies, so it was important to include the fish from other areas straying into the fishing districts that would be vulnerable to the fishing fleets in the run reconstruction.

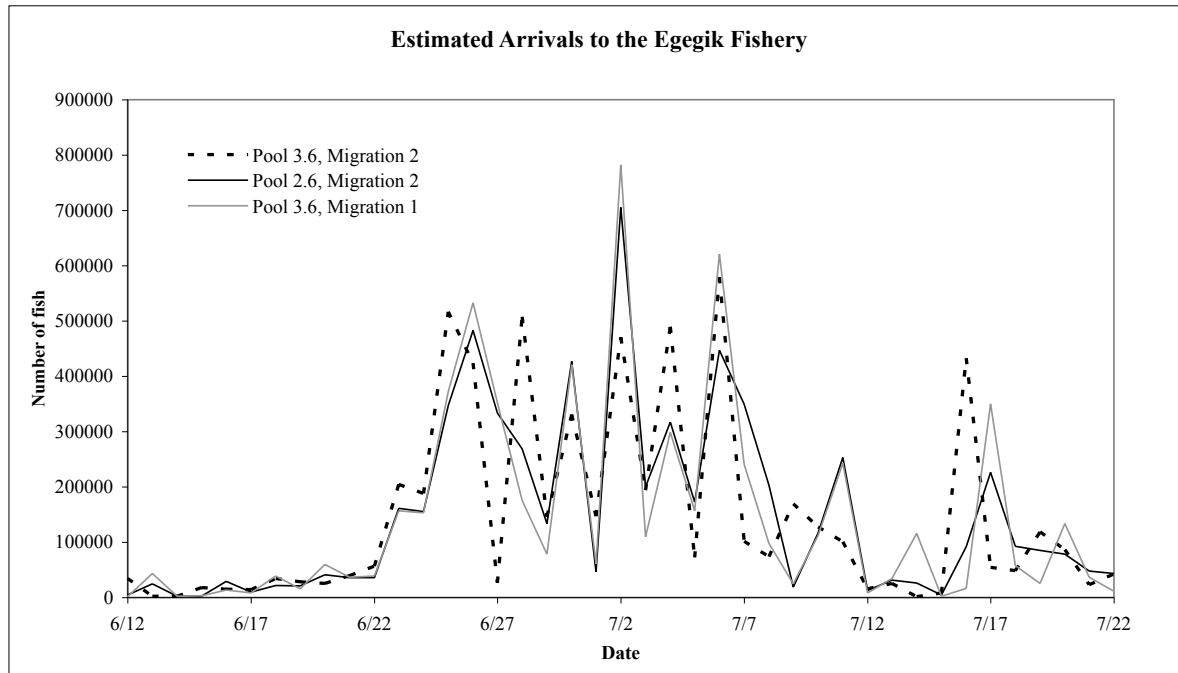
Regarding assumption iii), all fish are equally vulnerable to catch: gear used for catching fish (e.g., gillnets) is size selective, meaning every fish does not have the same probability of being caught. It is very difficult to account for this size

selectivity in the model without knowing the size distribution of the salmon run. All fish are either accounted for in the catch or escapement, so size selectivity will only affect the proportion of fish arriving on each day. Equal vulnerability can be assumed because the model is fairly robust to different pooling times, which should have a similar effect as slight variations in arrival density.

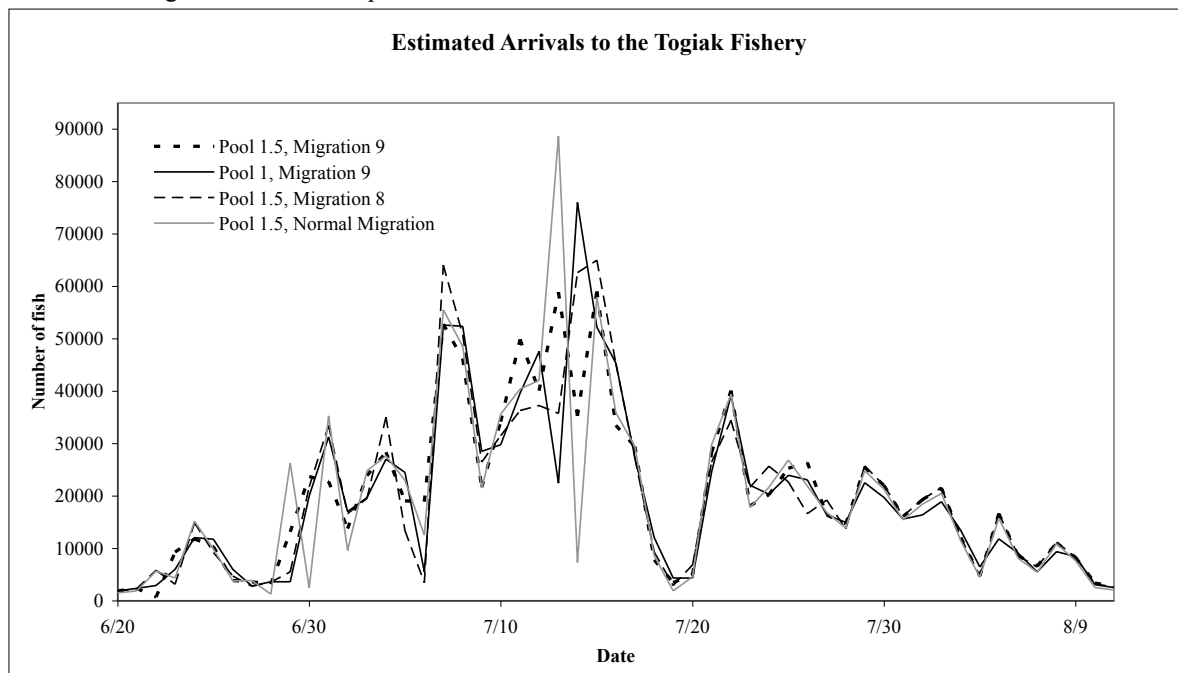
Regarding assumption vi), there is no mortality or interception during the migration: subsistence and sport fishing of sockeye salmon in Bristol Bay is negligible compared to the large commercial fishery, therefore interceptions during migration are considered insignificant. Some mortality may take place on the migration to the spawning ground. Both mortality or interception would lead to an underestimation of the run; however, since the run may be overestimated due to assumption ii, this should not have a significant effect on the run reconstruction.

Regarding assumption vii), the catch and escapement counts are accurate: tower counts are comparable to weir counts of salmon escapement. There is one counting tower on each side of the river, since returning sockeye salmon either migrate up one side of the river or the other (Anderson 2000). In 1956, a study was done to compare tower counts to weir counts, where returning salmon are counted directly by blocking passage of salmon upriver with a weir. Tower counts were 7.4% lower than weir counts; however, if the two days that fish were migrating on the opposite side of the river were taken out, the tower counts were only 1.1%

lower (Anderson 2000). The tower count can be assumed to be generally accurate, although the error will be different based on the observer and weather conditions.



**Figure 1.B-1. Egegik and Togiak Estimated Arrivals vs. Pooling and Migration Time.** Estimated arrivals to the Togiak fishery in 2003 and the Egegik fishery in 2010 with different pooling time and migration time assumptions.



**Figure 1.B-1. continued...**

**Table 1.B-1. Egegik Parameter Estimates vs. Pooling Time.** Effect of the pooling time assumption on the harvest fraction equation parameter estimates for Egegik.

Pooling Time	$b_{96}$	$b_{97}$	$q_d$	$q_s$
4.6 days	0.48	0.41	0.0051	0.00063
3.6 days	0.56	0.47	0.0057	0.00087
2.6 days	0.66	0.57	0.0072	0.00142

**Table 1.B-2. Togiak Parameter Estimates vs. Pooling Time.** Effect of the pooling time assumption on the harvest fraction equations parameter estimates for Togiak

Pooling Time	$b$	$q_d$	$q_s$
1	0.61	0.030	0.0175
1.5	0.58	0.019	0.0091
2	0.59	0.017	0.0082
3	0.51	0.014	0.0052

## Chapter 2:

### Using Model Simulations to Compare Two Commercial Salmon Management Strategies<sup>1</sup>

#### Abstract

Salmon fisheries in Alaska are managed on the sustained yield principle and guided by the Policy for the Management of Sustainable Salmon Fisheries. In this paper, we analyze the costs and benefits associated with "active management" and a fixed fishing schedule on the Egegik and Togiak sockeye salmon (*Oncorhynchus nerka*) fisheries in Bristol Bay, Alaska. In particular, we examine how these strategies affect the economics of the fishery and how they meet the requirements of Alaska's salmon management policies. To compare the two strategies, we simulated active management and a fixed fishing schedule on the two fisheries. Historically, Egegik used an active management strategy, while we found that the Togiak strategy was a hybrid between the two management strategies. Our simulations show that an active management strategy results in higher yearly catches, less yearly variation in escapement, and fewer years of escapement below the goal range. A fixed fishing schedule results in less yearly variation in catch and a more even harvest rate, with the evenness more pronounced when effort was held

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<sup>1</sup> Carney, J. M. and Adkison, M. D. 2013. Using model simulations to compare two commercial salmon management strategies. Prepared for submission to Canadian Journal of Fisheries and Aquatic Sciences.

constant. Potential benefits of active management over a fixed fishing schedule are that maximum sustained yield is more likely to be achieved, under escapement is less likely, and the productive capacity of the fishery may be better protected.

Potential benefits of a fixed fishing schedule are lower management costs, better maintenance of the genetic and phenotypic diversity and sex ratio, and more predictability for fishermen and processors. Active management is a desirable strategy for fisheries that are managed for maximum sustained yield, have high fishing effort, a small fishing area, or a more temporally compressed run. A fixed fishing schedule is a desirable strategy for fisheries with less intense effort, budgetary or efficiency concerns, or stock components that differ in run timing.

### **Introduction**

Salmon (*Oncorhynchus spp.*) fisheries in Alaska are managed on the sustained yield principle and guided by the Policy for the Management of Sustainable Salmon Fisheries (State of Alaska 2010, provision 5 AAC 39.222). The goal of this policy is to, "ensure conservation of salmon and salmon's required marine and aquatic habitats, protection of customary and traditional subsistence uses and other uses, and the sustained economic health of Alaska's fishing communities." Five of the principles and criteria guiding this management (from the policy mentioned above) are: i) unless otherwise directed, manage for maximum sustained yield (MSY), ii) manage to maintain diversity, including managing escapement to, "maintain genetic and phenotypic characteristics of the stock by assuring appropriate geographic and temporal distribution of spawners as well as consideration of size range, sex ratio,



and other population attributes," iii) conduct research and data collection to improve scientific and technical knowledge, iv) manage with a precautionary approach, with priority given to conserving the productive capacity of the resource, and v) prevent overfishing.

The sustained yield principle is applied by establishing escapement goal ranges, i.e., numbers of fish that arrive at the spawning grounds, for stocks of salmon and managing to maintain escapement within that goal range (State of Alaska 2010, provision 5 AAC 39.223). "Biological escapement goals" are established for stocks managed for MSY. "Sustainable escapement goals" are established for stocks where a biological escapement goal cannot be estimated or managed for; these goals must be known to provide for sustained yield over a 5 to 10 year period. "Optimal escapement goals" are established for stocks managed to achieve a specific management objective other than MSY, "such as achievement of a consistent level of sustained yield, protection of a less abundant or less productive salmon stock or species, enhancement of catch per unit effort in sport fishery, facilitation of a non-consumptive use, facilitation of a subsistence use, or achievement of a specific allocation."

Two management strategies employed in Alaska to achieve sustained yield are "active management" and a fixed fishing schedule. The primary goal of commercial salmon managers is to meet the escapement goal range. "Active managers" use emergency order authority to open and close commercial fisheries based on estimates of the current year's escapement and run strength to meet the

goal range (Clark et al. 2006). In contrast, a fixed fishing schedule allows fishing, to the extent practical, on fixed days of the week (State of Alaska, provision 5 AAC 06.369); the fixed fishing schedule can be modified using emergency order authority when necessary to meet the escapement goal range.

Active management is more expensive than a fixed fishing schedule. Active management requires in-season information such as estimates of run strength and escapement that are rapidly updated throughout the season (Clark et al. 2006). Preseason estimates are based on previous years' returns, which require sampling the commercial catch and escapement for analysis and aging. Escapement estimates (commonly in the form of tower counts, weir counts, aerial surveys, or sonar counts), analyses of the current year's catch and escapement, and test fishing (where fishing vessels catch fish before they reach the fishing grounds, e.g., sampling at Port Moller for salmon bound for Bristol Bay) are used to update the run strength and escapement estimates. In-season genetic analyses of the test fishing catches have recently been used in Bristol Bay to determine the proportion of fish heading to each fishing district, which requires airlifting samples to a genetics laboratory in Anchorage (Dann et al. 2009). Because a fixed fishing schedule does not require any of these things, the management costs are much lower, although escapement estimates are still needed to evaluate the performance of the fixed fishing schedule.

## **Management strategy comparison**

Management evaluations can be separated into two main classifications: model-based approaches and empirical approaches. Empirical studies use observable data to analyze the results of a management approach, e.g., the number of returning spawners. Model simulations base the evaluations on population dynamics models, although usually the models are based on data. Model-based management strategies are more common than empirical approaches because models allow for comparisons of strategies that may not have empirical evidence and model-based approaches have been shown to outperform empirical-based strategies in limiting the variability of catch (Punt 2006). There are four key aspects of a model simulation to evaluate management strategies: i) to specify and quantitatively represent management goals, ii) to have a sufficiently complicated model that accounts for the main biological processes and uncertainties, iii) to simulate the data used by managers, and iv) to test the sensitivity of the model to different assumptions. Adkison (2009) showed that management strategies based on simple models could outperform those based on complex models, in terms of average yield of fish, even if the additional complexity more accurately describes the population dynamics. Additional parameters cause added uncertainties that can negate the benefits of a more realistic model. Fisheries models used in management strategy evaluation need to simulate the stochastic nature of a population, observation error, estimates of manager's decisions, the deviation in their execution, and the effects on the population (Peterman 2004).

In this paper, we analyze the costs and benefits of active management and a fixed fishing schedule, particularly in relation to the economics of the fisheries and meeting the requirements of Alaska's salmon management policies. By simulating active management and a fixed fishing schedule for the Egegik and Togiak fisheries, we can compare the differences between the two strategies within each fishing district. The implications of a management strategy are dependent on the attributes of the particular fishing district. We develop a list of attributes of a fishery conducive to an active management or fixed fishing schedule strategy.

## **Materials and methods**

### **Study site**

The two study sites are the Egegik and Togiak Fishing Districts in Bristol Bay, Alaska (Figure 2.1). Egegik and Togiak are ideal study locations because they both have one major river that sockeye salmon (*Oncorhynchus nerka*) return to (the Egegik and Togiak Rivers, respectively), while being managed with contrasting management strategies (active management and, to the extent practical, a fixed fishing schedule, respectively). The Egegik and Togiak escapement goal ranges are listed as sustainable escapement goals (Baker et al. 2009). The escapement goal range is 800 000 to 1 400 000 for the Egegik River, while the Togiak goal is 100 000 to 250 000 in tower counts plus 20 000 fish spawning below the counting tower.

### **Data**

Daily effort data were provided by Paul Salomone (Alaska Department of Fish and Game (ADF&G, Anchorage). The estimated number of drift gillnet vessels

and set gillnet permits (derived from the daily effort data) and the estimated daily fish arrivals ( $N_t$ ) were taken from Carney and Adkison (Chapter 1).

Effort data were only recorded when fishing was allowed. In order to base our retrospective simulations on historical fleet size, we needed to create realistic effort levels for days when no fishing occurred historically. Therefore, the observed effort values were interpolated and extrapolated so that effort levels would be available if, in the simulation, fishing occurred. The effort series were constructed each year for dates from June 12th to July 22nd and June 20th to August 11th for Egegik and Togiak, respectively.

Shepard's method was used to interpolate between effort values (Shepard 1968). Shepard's method is a  $k$ th-nearest neighbor approach with inverse distance weighting. Nearest neighbor methods are commonly used with data that have similarities between points close together, such as spatial point processes, cluster analysis, and density analysis (El-Shaarawi and Piegorsch 2002). The daily effort values are related because set gillnets that fished the previous day are registered to fish in the same fishing district the next day, as are drift vessels unless they choose to transfer to another district. We chose to use the four closest points, two on each side (or three closest points if either side had only one closest value), because this allowed quick calculation, while decreasing the weight of outlier effort data. We chose inverse square root of distance weighting to increase the smoothness of the interpolation function by giving less weight to the outlier peaks and valleys (Shepard 1968, Breiman et al. 1977). The interpolated effort value was calculated as

$$\hat{E}_i = \frac{\sum_{n=1}^4 w_n E_n}{\sum_{n=1}^4 w_n} \quad (2.1)$$

where  $\hat{E}_i$  was the estimated effort on day  $i$ ,  $E_n$  was the observed effort on day  $n$ , where  $n$  represented the dates of the four (or three) closest points with observed effort data, and

$$w_n = \frac{1}{\sqrt{|n - i|}} \quad (2.2)$$

For extrapolation prior to and after observed fishing effort, a different method was used. The first and last dates fished for the drift gillnet and set gillnet fleets were not always the same. Whichever effort series started later (or ended earlier) was extrapolated an additional four days. If necessary, the other series was extrapolated to match the beginning (or end) date. If the start (or end) dates were the same for the drift and set gillnet fleets, both effort series were extrapolated four days. Earlier or later efforts were set to zero.

When drift vessel registration data was available, the registered number of drift vessels was used to extrapolate the missing drift effort values. When there was no registration data the first or last effort value was repeated to extrapolate the missing effort values. For set net effort, the first or last effort value was always used for extrapolation.

### Fisheries dynamics model

The fisheries dynamics model from Carney and Adkison (Chapter 1) was adapted to a forward simulation by varying the expected harvest rate stochastically. The total number of fish available for harvest on a given day  $i$  was calculated as

$$(2.3) \quad X_i = \sum_{t=1}^i N_t - \sum_{t=1}^{i-1} \hat{C}_t - \sum_{t=1}^{i-1} \hat{S}_t$$

where  $N_t$  is the number of fish arriving on day  $t$ ,  $\hat{C}_t$  is the predicted number of fish caught on day  $t$ , and  $\hat{S}_t$  is the predicted escapement from the fishery on day  $t$ . The expected harvest rate for day  $i$  ( $\hat{h}_i$ ) was calculated as

$$(2.4) \quad \hat{h}_i = b \left( 1 - e^{-q_d E_{i,d}} \right) + \left[ 1 - b \left( 1 - e^{-q_d E_{i,d}} \right) \right] \left( 1 - e^{-q_s E_{i,s}} \right)$$

where  $b$  is a drift fleet efficiency parameter (with Egegik having a separate efficiency parameter for years 1996 and earlier,  $b_{96}$ , and for years 1997 and later,  $b_{97}$ ),  $q_d$  is the catchability coefficient for the drift gillnet fleet,  $q_s$  is the catchability coefficient for the set gillnet gear,  $E_{i,d}$  is the drift effort on day  $i$ , and  $E_{i,s}$  is the set gillnet effort on day  $i$ . Egegik had a separate efficiency parameter for years after 1996 because in 1997 the Alaska Board of Fisheries changed management of the district to allocate 14% of the catch to set gillnet gear; previously, there was no allocation goal (State of Alaska, provision 5 AAC 06.365). The actual harvest fraction for day  $i$  ( $h_i^*$ ) was calculated as:

$$(2.5) \quad h_i^* = \hat{h}_i e^{\left(\delta_i - \frac{\sigma_f^2}{2}\right)}$$

where  $\hat{h}_i$  was the expected harvest fraction,  $\delta_i$  was a random normal number with mean zero and variance  $\sigma_f^2$ , and  $\sigma_f$  was the standard deviation of the difference between the Carney and Adkison (Chapter 1) predicted and observed harvest fraction recorded from 1986-2010 (equal to 0.15 and 0.11 for Egegik and Togiak, respectively). The catch was calculated as

$$(2.6) \quad \hat{C}_i = h_i^* X_i$$

The expanded tower counts of escapement were calculated as

$$(2.7) \quad \hat{T}_i = c \hat{S}_{i-j}$$

where  $\hat{S}_{i-j}$  is the predicted escapement on day  $i-j$ ,  $\hat{T}_i$  is the predicted expanded tower count on day  $i$ ,  $j$  is the migration time from the fishery to the tower, and  $c$  is the proportion of the escaping fish that reach the tower. The migration time from the fishery to the tower was estimated as two and nine days for the Egegik and Togiak Rivers, respectively (Flynn et al. 2006, Brannian 1982). All of the fish that escape the fishery in the Egegik were assumed to reach the counting tower (i.e.,  $c = 1$ ). The estimate of  $c$  for Togiak was 0.9 because Togiak has an escapement goal of 20 000 fish spawning below the counting tower, which represents approximately 10% of the mean historical tower counts. The proportion of fish leaving the fishery was calculated as



$$(2.8) \quad P_{i,t} = \begin{cases} 0 & \text{for } t < k \\ 2\left(\frac{i-f}{l-f}\right)(1-r) & \text{for } t = k \\ \text{the remaining fish} & \text{for } t = k + 1 \end{cases}$$

where  $P_{i,t}$  is the proportion of fish that arrive on day  $i$  and escape after spending  $t$  days pooling,  $f$  is the date when 2.5% of the total run had reached the fishery,  $l$  is the date when 97.5% of the total run had reached the fishery, and the mean number of days spent pooling in the fishery was broken up into  $k$  being the whole number of days and  $r$  the remainder. The mean number of days spent pooling in the fishery was assumed to be 3.6 (i.e.,  $k = 3$  and  $r = 0.6$ ) and 1.5 days for the Egegik and Togiak, respectively (Flynn et al. 2006, Carney and Adkison (Chapter 1)).

### Active management simulation

The Egegik District is currently managed with an active management strategy; therefore, the algorithm for simulating active management was based on the behavior of the Egegik District managers.

Our examination of historical data suggested that the Egegik District managers were more conservative (fished less frequently) early in the season (Figure 2.2); they also generally allowed fishing three days per week before escapement was recorded. We modeled the observed shift in management behavior by having two critical values to determine when fishing was allowed, one early in the season and one later in the season. Thus, the simulated active managers' behavior allowed fishing for three days per week before there was escapement data; after there was escapement data, they allowed fishing on day  $i+1$

$$(2.9) \quad \begin{array}{ll} \text{if } ET_i > ET_{early} & \text{when } i - f_e < m \\ \text{if } ET_i > ET_{late} & \text{when } i - f_e \geq m \end{array}$$

where  $ET_{early}$  and  $ET_{late}$  were critical values that determine when fishing was allowed,  $i$  was the date,  $f_e$  was the first day of escapement,  $m$  was the cumulative number of days of escapement data prior to a shift in manager's behavior, and  $ET_i$  was the performance indicator on day  $i$ , calculated as

$$(2.10) \quad ET_i = \frac{\left( \sum_{t=f}^i \hat{T}_t - G_i \right)}{G_l} * 100\%$$

where  $\hat{T}_i$  is the predicted tower count on day  $i$ ,  $G_i$  is the expected cumulative tower count on day  $i$  under average run timing, and  $G_l$  is the expected cumulative tower count on the last day of the simulation under average run timing. Simulations with two  $ET$  values outperformed those with one (see Results); no simulations were run with more than two  $ET$  values. The average run timing for the tower count was calculated as a normal distribution with a yearly mean date,  $\mu_y$ , and a year-invariant standard deviation,  $\sigma$  (8.02 days for Egegik and 10.67 days for Togiak). The mean date,  $\mu_y$ , was a ten-year running average of the mean total run timing date delayed for the time spent migrating from the fishery to the counting tower. The yearly mean total run timing dates for 1986-2010 were taken from Carney and Adkison (Chapter 1); values for previous years were calculated by assuming normal arrival timing for the cumulative catch plus escapement, with  $\sigma$  used as the standard deviation for each year. The performance indicator is an approximation of actual

managers' behavior because the actual managers set fishing openings and closings based on the likelihood of the final escapement being within the goal range given the escapement up to date and estimates of the current year's run strength and timing (based on past runs and the run strength to date of the current year).

The active management strategy was simulated on the actively managed Egegik fishery to both calibrate and determine the reasonableness of the model, comparing the simulated management to that of the real-world managers. The simulations were for 41 days, June 12th to July 22nd, from 1986-2010.

We selected values for Egegik of  $ET_{early}$ ,  $ET_{late}$ , and  $m$  that resulted in simulations that matched key aspects of the observed historical behavior of management in Egegik. The range of values we explored was 5 to -25%, -10 to -25%, and 6 to 15 days for  $ET_{early}$ ,  $ET_{late}$ , and  $m$ , respectively. The Egegik managers met the minimum escapement goal every year between 1986-2010, so the best values needed to produce an average of zero escapements below the goal range over 100 simulations. Of the simulations that averaged zero years of escapement below the goal range, the best values for Egegik were chosen as those that minimized the simple sum of squares of the difference between the natural logarithms of the observed and predicted yearly catches and yearly escapements.

$$(2.11) \quad SSQ = \sum \left( \ln(C_y) - \ln(\hat{C}_y) \right)^2 + \sum \left( \ln(T_y) - \ln(\hat{T}_y) \right)^2$$

where  $C_y$  was the observed sum of catch for year  $y$ ,  $\hat{C}_y$  was the predicted sum of catch for year  $y$ ,  $T_y$  was the observed sum of tower counts for year  $y$ , and  $\hat{T}_y$  was the predicted sum of tower counts for year  $y$ .

The Togiak District is currently managed by a fixed fishing schedule, so an active management strategy was simulated on the runs from 1986-2010; the simulations were for 53 days, June 20th to August 11th. The chosen values for  $ET_{early}$ ,  $ET_{late}$ , and  $m$  from the Egegik simulations were used as starting values for the Togiak simulations; the parameter values were increased and decreased by one unit until the simulations resulted in an average of zero years of escapement below the goal range. Parameter values were varied further if the new parameter values increased the mean yearly catch.

### **Fixed fishing schedule simulation**

The Egegik District is currently managed through the use of emergency order openings, so a fixed fishing schedule was simulated on the runs from 1986-2010; the simulations were for 41 days, June 12th to July 22nd. The fixed fishing schedule simulations used the same fisheries dynamics model as the active management simulations. Fishing was allowed for a fixed number of days per week, ranging from one to seven. Current regulations allow for variable effort, therefore two different effort scenarios were explored. The first scenario allowed for effort to change; historical effort (interpolated and extrapolated) was used for the daily effort, as this should at least partly account for the attractiveness of Egegik relative to neighboring

districts. The second scenario assumed new regulations to maintain a constant effort; the effort was equal to the mean effort from years 2006-2010.

A fixed fishing schedule, from one to seven days per week, was simulated on the Togiak fishery as a comparison to the historical fishing schedule. Historical effort (interpolated and extrapolated) was used for the daily effort. The most appropriate fishing schedule was determined as the schedule that had a mean number of years of escapement below the goal range closest to that of the historical record and that minimized the simple sum of squares of the difference between observed and predicted yearly catches and yearly escapements (the same method used for the Egegik active management simulations).

### **Management strategy comparison**

The two management strategies were compared based on the mean and coefficient of variation (CV) of the simulated yearly catches and escapements, the number of years of escapement above and below the goal range, and the cohort harvest fraction throughout the season. The chosen strategies for active management and a fixed fishing schedule were compared over 1 000 simulations. The cohort harvest fraction on a particular date was the percentage of fish that arrived on that date that were caught while pooling in the fishery, averaged across all simulations.

## Results

### Active management simulation

The yearly catch totals from the active management simulations on the Egegik fishery followed the historical totals closely; the fits of the yearly escapement totals were not as exact, but they were within the escapement goal range (Figure 2.3). The values from the Egegik simulations that best matched the criteria for fit were between -3 and -9%, -20 and -22%, and 9 and 10 days for  $ET_{early}$ ,  $ET_{late}$ , and  $m$ , respectively. Of the values that resulted in zero years of escapement below the goal range, the set of values that were closest to the observed yearly catches and escapements were -3%, -20%, and 9 days for  $ET_{early}$ ,  $ET_{late}$ , and  $m$ , respectively. None of the models with only one  $ET$  value were amongst the top models. The simulated active management reproduced the total yearly catches more closely than the total yearly escapements ( $R^2$  values of fit of 0.96 and 0.23 for total yearly catches and escapements, respectively). The actual and simulated managers manage on a fixed escapement policy with a narrow goal range. Therefore, much of the fluctuations in run size translate to fluctuations in catch. The  $R^2$  values are higher for catches than for escapements because much of the variability in catches is intrinsically explained by the fluctuations in run size.

The best values for Togiak were similar to the best values for Egegik, but the  $m$  value was more cautious; the best values for Togiak were -2%, -33%, and 11 days for  $ET_{early}$ ,  $ET_{late}$ , and  $m$ , respectively (Table 2.1). The  $ET_{late}$  value from Egegik

seemed more cautious because if the tower count was below the daily goal by more than about 20 percent of the final goal fishing was not allowed, compared to 33 percent for Togiak; however, they both would result in escapement above the lower end of the goal range. The best  $m$  value for Togiak required one to two more days with tower counts before switching to the less cautious critical value than the best values for Egegik.

### **Fixed fishing schedule simulation**

The Egegik variable effort simulations caught more fish than the constant effort simulations for a given fixed fishing schedule (Table 2.2). However, the fixed fishing schedule simulations with constant effort resulted in higher average catches than the simulations with the varying historical effort, presumably reacting to run size, because the most appropriate schedule fished more days per week (Table 2.3). The constant effort simulations resulted in fewer years of escapement below the ADF&G goal range than the corresponding fixed schedule with historical, variable effort; therefore, when effort was constant, the fishing fleets could fish more days per week with a similar risk of escapement below the goal range (Table 2.2). Historically, the fixed fishing schedule in Togiak resulted in one year out of 25 with escapement below the goal range; a four day per week and five day per week fishing schedule in the Egegik simulations, for variable effort and constant effort, respectively, also resulted in an average of one year of escapement below the goal range (Table 2.2).

The most appropriate fixed fishing schedule for the Togiak District allowed fishing for five days per week, Monday-Friday. With a fishing schedule of four days per week (Monday-Tuesday and Thursday-Friday), the mean number of years of escapement below the goal range was closer to the historical number than a fishing schedule of five days per week was (1.01, 2.00, and 1 for the four day per week, five day per week, and historical schedules, respectively). However, the sum of squares of the difference between the natural log of the observed and predicted yearly catches and yearly escapements for the four day per week schedule was more than double that of the five day per week schedule (1.61 and 3.28 for the five and four day per week schedules, respectively), indicating a much poorer match to the observed yearly catch and escapement totals.

### **Management strategy comparison**

In both fishing districts, the active management strategy caught more fish than the fixed schedule strategy, but the catch was more variable (the CVs were 0.03-0.07 and 0.08 higher for the Egegik and Togiak simulations, respectively) (Table 2.3). Escapement was higher and more variable with the fixed schedule than with active management (the CVs were 0.07-0.13 and 0.06 higher for the Egegik and Togiak simulations, respectively) (Table 2.3). The active management strategies had fewer years of escapement below the goal range and fewer years above the goal range.

The cohort harvest fraction curve for the fixed fishing schedules was smoother with a smaller range than the curve for active management for the Egegik



and Togiak simulations (Figures 2.4 and 2.5). Cohort harvest fractions ranged from [0.31, 0.82], [0.73, 0.84], and [0.28, 0.89] for a fixed fishing schedule with variable effort, a fixed fishing schedule with constant effort, and active management, respectively, for the Egegik simulations and [0.20, 0.62] and [0.17, 0.73] for a fixed fishing schedule and active management, respectively, for the Togiak simulations. The smaller range and smoothness of the harvest fraction curve were more pronounced when effort was held constant; this indicates that part of the unequal harvest rate is due to in-season changes in effort, and not solely due to changes in the fishing strategy.

The historical fishing schedule for the Togiak fishery was a hybrid between a fixed fishing schedule and active management. Historically, the Togiak fishery operated as a fixed fishing schedule, but the schedule could be modified by emergency order to help ensure escapement was within the goal range. Not surprisingly, the results of the historical fishing schedule for the Togiak fishery were in between the results for the fixed fishing schedule and active management simulations (Table 2.3). The historical fishing schedule for the Egegik fishery was active management. The results of the historical fishing schedule for the Egegik fishery were closer to the active management simulations than the fixed fishing schedule simulations (Table 2.3).

## **Discussion**

Both active management and a fixed fishing schedule offer predictability, but in different areas. With active management, there is less annual variation in

escapement and the escapement is more likely to be in the goal range than with a fixed fishing schedule. With a fixed fishing schedule, there is less annual variation in catch, although there is also a lower annual mean. With a fixed fishing schedule, the harvest rate is spread more evenly throughout the season than with active management; there is even more predictability in harvest rate if effort is constant throughout the season.

### **Policy and economic implications**

Although there are potential benefits to a fixed fishing schedule in Egegik, new regulations would be needed to allow it. Current policy (State of Alaska, provision 5 AAC 39.222) states that salmon fisheries in Alaska are to be managed for MSY unless other objectives of the fishery oppose MSY. Active management is more likely to achieve MSY than a fixed fishing schedule because there is greater control over catch and escapement. Therefore, a fixed fishing schedule in Egegik would only make sense based on other objectives; these objectives could include economic benefits for the fishing community (Steiner et al. 2011), enhancement of catch per unit effort, or allocation. If the new management objectives required a different escapement goal range, the sustainable escapement goal would need to be changed to an optimal escapement goal.

New regulations would also be needed if constant fishing effort were desired in Egegik. Currently, drift vessels registered in Bristol Bay, except those registered in the Togiak District, can switch to the Egegik District with only a 48-hour penalty

between June 25 and July 17 and no penalty outside those dates (State of Alaska, provision 5 AAC 06.370).

An active management strategy is economically viable in Egegik, but probably not in Togiak. We calculated rough estimates of management costs for the Egegik and Togiak fisheries with the help of the local managers (Paul Salomone and Matt Jones, ADF&G Anchorage, for Egegik and Togiak, respectively). The management costs for Egegik are roughly \$292 000, including operation of the counting tower, in-river test fishing, salaries of personnel, and a percentage of the Port Moller test fishing (based on the percentage of the annual catch). The management costs for Togiak are roughly \$120 000, including operation of the counting tower, salaries of personnel, commercial catch sampling, and aging and analysis of the tower and commercial catch samples, a difference of \$172 000. The active management simulations in Egegik caught an average of 607 000 and 299 000 more fish than the fixed fishing schedule simulations, for variable and constant effort scenarios, respectively. The average sockeye salmon in Bristol Bay from 1994-2010 weighed 5.93 pounds and the average ex-vessel value per pound from 1986-2010 was \$0.90, for an average of \$5.34 per fish (ADF&G website). Thus, crude calculations suggest that an active management strategy might yield an average of \$3 200 000 and \$1 600 000 of additional ex-vessel value per year than a fixed fishing schedule, for variable and constant effort, respectively (Steiner et al. note that processing capacity limitations might prevent some of these additional harvests from being realized). In contrast, the active management simulations in Togiak

caught an average of 20 000 more fish than the fixed fishing schedule simulations, resulting in only an additional \$108 000 in ex-vessel value. The added ex-vessel value in Egegik more than covers the additional management costs, while the added ex-vessel value in Togiak does not. Even if the management costs for a fixed fishing schedule were zero, the additional ex-vessel value in Egegik would more than cover the added cost.

The management costs of a strict fixed fishing schedule in Togiak might be less than the current costs of the hybrid strategy. In theory, a fixed fishing schedule does not require escapement estimates such as tower counts, commercial catch sampling, and associated aging or genetics work, and these could therefore be saved from the budget. However, the tower counts and commercial catch sampling help meet the Sustainable Salmon Policy's mandate to research and collect data to improve the scientific and technical knowledge of salmon fisheries, including the status of salmon populations. In addition, escapement estimates are needed to evaluate management's success or failure in meeting the escapement goal range.

A fixed fishing schedule might better maintain the genetic and phenotypic diversity and sex ratio of a salmon stock. The Sustainable Salmon Policy states that escapement should be managed to maintain genetic and phenotypic diversity, including temporal distribution of spawners and the sex ratio. The harvest rate was more evenly spread throughout the season with a fixed fishing schedule than with active management, which would provide a more temporally representative group of spawners. Different stocks and substocks may have different arrival timings and

males tend to arrive earlier than females, so both genetic diversity and sex ratio should be better protected with the more constant harvest rate of a fixed fishing schedule (Hendry and Day 2005, Morbey 2000).

The productive capacity of the salmon stock might be better protected and overfishing would be less likely with active management than with a fixed fishing schedule. Active management allows for greater control of escapement; the active management simulations resulted in fewer years with escapement below the ADF&G goal range than the fixed fishing schedule simulations for both Egegik and Togiak. Maintaining a large enough spawning population is one way to help ensure a high productive capacity of the salmon stock.

A fixed fishing schedule offers more predictability for fishermen and processors than active management. Under a fixed fishing schedule, fishermen and processors can be better prepared for the season because fishermen know what days they will be fishing and processors know what days fish will be delivered before the season starts. Processors would need fewer workers during the peak of the run because the off days in a fixed fishing schedule would allow the processors to catch up if there were periods of large catches. However, the work would be more consistent for the processors because fishing would be allowed even when the run is small and the harvest would be spread more evenly throughout the season. Overall there would likely be a net economic gain for the processors, but the gain would be spread among fewer individuals.

## **Model assumptions**

Four assumptions of these model simulations are: i) the fisheries dynamics model reasonably approximates the fishery and fish arrival, ii) the interpolation and extrapolation methods give reasonable estimates of what effort would have been if fishing had been allowed, iii) the residuals of the difference between the observed and expected harvest fractions are stochastic and normally distributed, iv) our simulated active management approximates what a real-world manager would do under the same circumstances. The goal of the simulations was to compare the two different management strategies; while there are undoubtedly some differences between our simulations and the real-world fishery, an assessment of these assumptions suggests that these would have a minimal effect on the resulting management strategy comparison.

The assumptions of the fisheries dynamics model are discussed in Carney and Adkison (Chapter 1). For interpolating effort, a nearest neighbor approach is sensible because the observed effort on a particular date is associated with the effort on near dates. The effort series tend to have a ramp-up and ramp-down period at the beginning and end of the run with less variable values in the middle of the run. Most of the extrapolations occur before the ramp up or after the ramp down, so repeating the last value is appropriate because the effort values are low during these periods with less variation.

The actual harvest rate in the model has a stochastic nature. It is possible that other parts of the model have a stochastic nature as well; however, only

building stochasticity into the harvest rate likely provides an accurate enough model to compare the two management strategies. The residuals of the difference between the historical observed and expected harvest fractions were skewed to the positive side with means of 0.02 (Figure 2.6). However, the equation to calculate the actual harvest fraction is also skewed positively, but with a mean difference of zero. Figure 2.2 shows the historical active management strategy in Egegik was more cautious early in the season; we represented this with two *ET* values. Model simulations with two *ET* values were closer to the historical records than those with one value, even when accounting for the added parameters.

The actual managers' behavior is much more complicated than the approximation used in the simulations. The actual managers use more information and continuously update throughout the season. However, our approximation probably represents the essential features well enough to give a reasonable estimate of the difference between active and passive management. For example, the active management simulations in Egegik gave similar results to the historical active management strategy in terms of in-season catch and escapement.

### **Strategy recommendations based on fishery attributes**

Active management would be a desirable strategy for fisheries that are managed for MSY, have high fishing effort, a small fishing area, or a more temporally compressed run. Fisheries with high effort and a small fishing area are more likely to be overfished and active management is more likely to prevent overfishing.

Active management is more likely to meet MSY than a fixed fishing schedule. If the

run is more temporally compressed, a higher harvest rate may be needed to catch enough fish to keep escapement below the upper end of the goal range and enhance the ex-vessel value of the fishery.

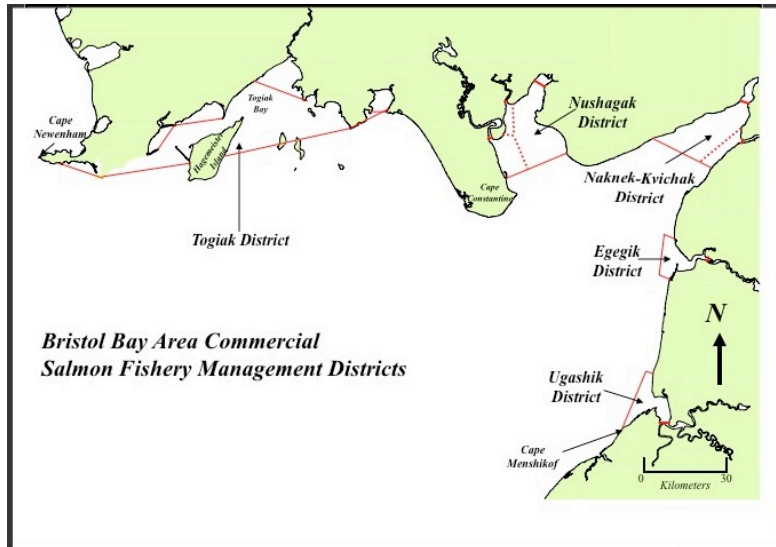
A fixed fishing schedule would be a desirable strategy for fisheries with less intense effort, budgetary or efficiency concerns, or stock components that differ in run timing. In low-value, low effort fisheries, the added cost of active management might not be offset by additional catch. If there are severe constraints in the management budget, a fixed fishing schedule can provide a satisfactory outcome even in areas better suited to active management, as we have shown for Egegik. A fixed fishing schedule provides more predictability for fishermen and processors than active management and can improve the profitability of the fishery (Steiner et al. 2011).

### **Acknowledgements**

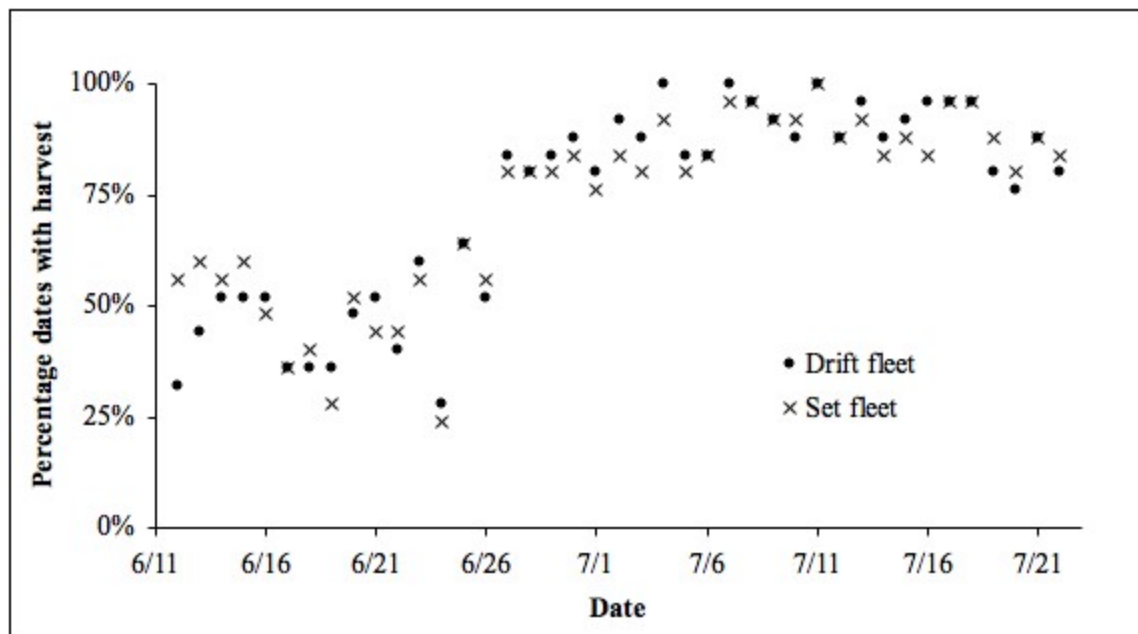
Alaska Sea Grant provided the funding for this project. This work benefited greatly from the guidance of Tim Baker, Megan McPhee, and Terry Quinn and support during the initial stages by Doug Molyneaux. Data and expertise on the study sites was given by Matt Jones, Paul Salomone, and Tim Sands. The map of the Bristol Bay fishing districts was provided by Daniel Gray.



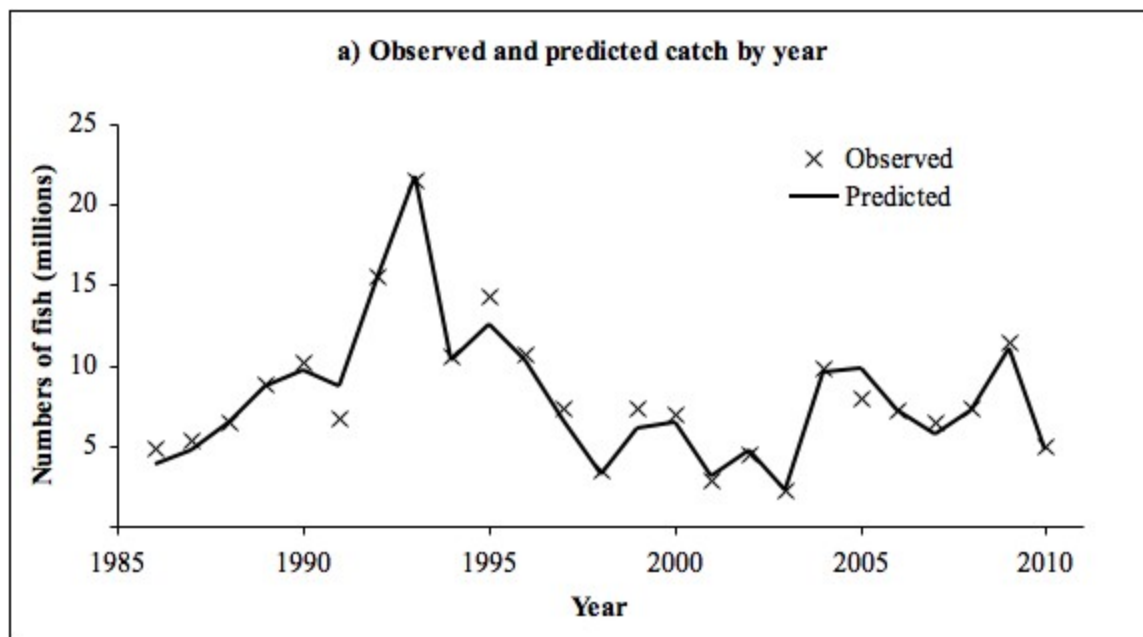
## Figures



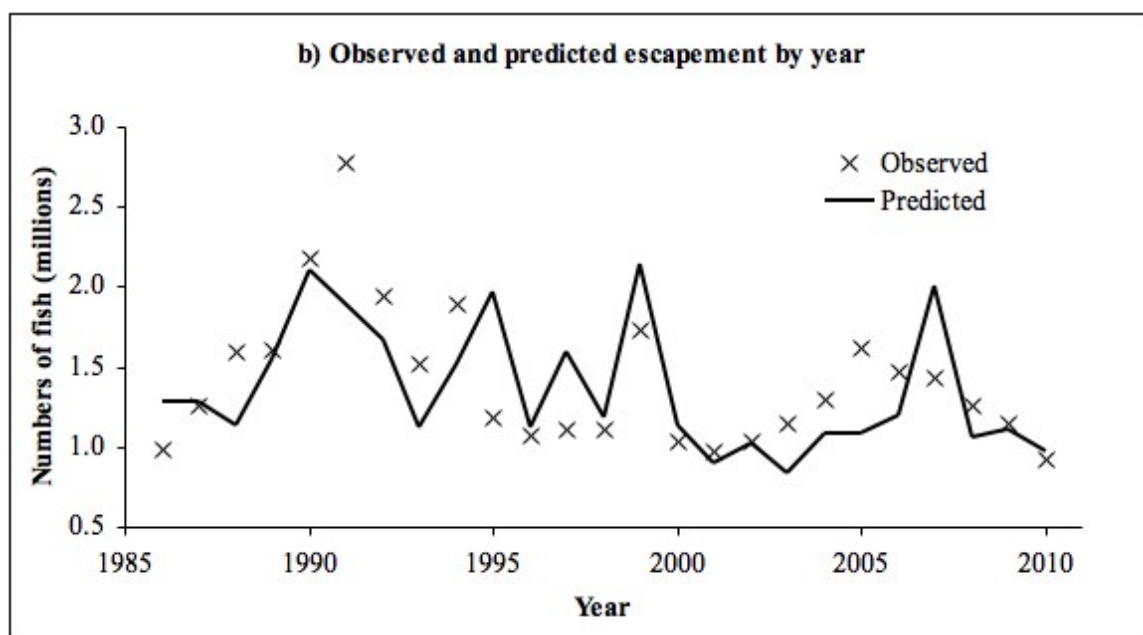
**Figure 2.1. Bristol Bay Map.** Map of the commercial fishing areas in Bristol Bay, Alaska. Produced by ADF&G.



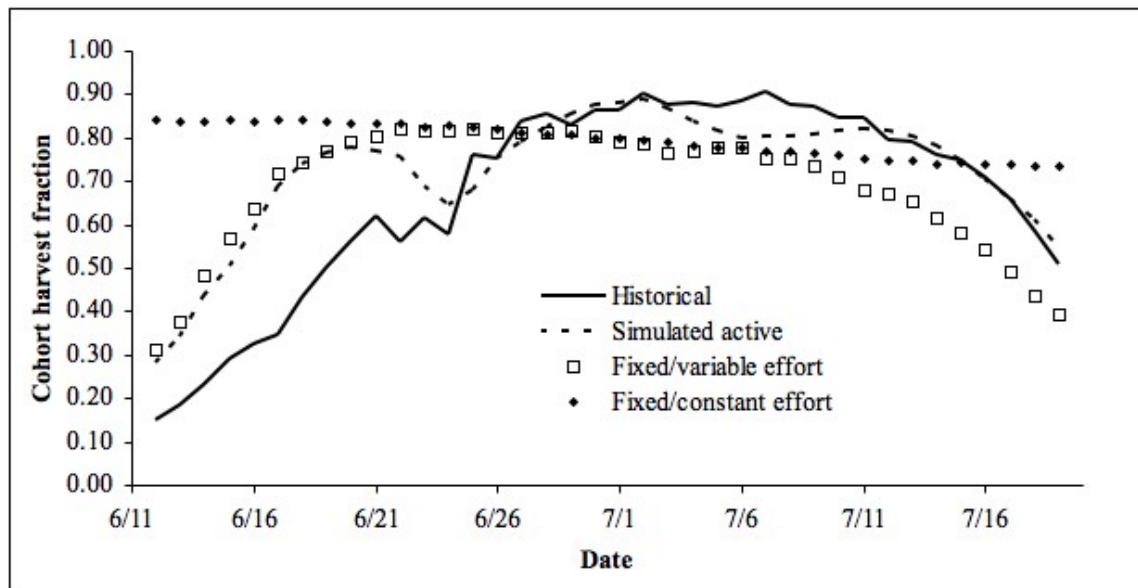
**Figure 2.2. Percentage of Egegik Fisheries Openings by Date.** The percentage of the years that fishing was open for a given date for the drift and set gillnet fleets for the Egegik District from 1986-2010.



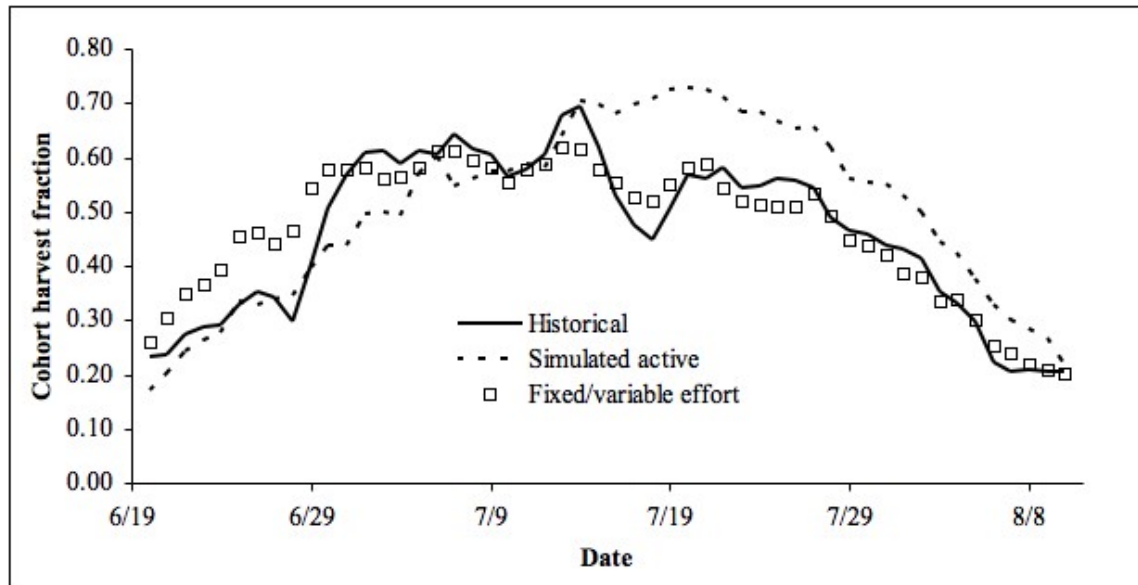
**Figure 2.3. Egegik Observed and Predicted Catch and Escapement.** The observed (historical) and predicted (active management simulations) (a) catch and (b) escapement of the Egegik District.



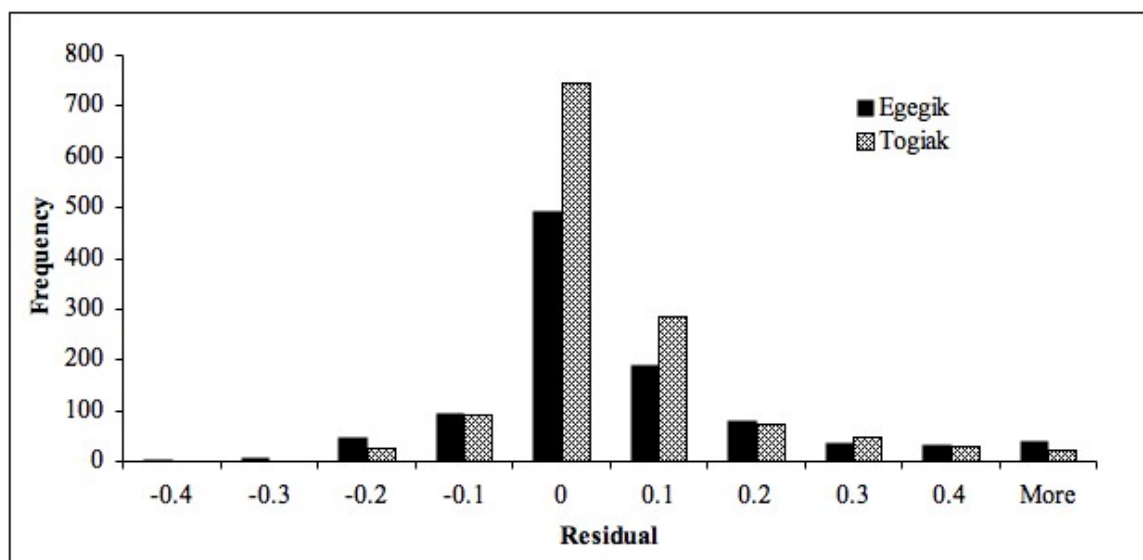
**Figure 2.3. continued...**



**Figure 2.4. Egegik Cohort Harvest Fraction.** Average cohort harvest fraction by date for the active management and fixed fishing schedule with variable or constant effort simulations and the historical fishing schedule for the Egegik fishery.



**Figure 2.5. Togiak Cohort Harvest Fraction.** Average cohort harvest fraction by date for the active management and fixed fishing schedule with variable effort simulations and the historical fishing schedule for the Togiak fishery.



**Figure 2.6. Run Reconstruction Harvest Fraction Residuals.** The frequency of the residuals of the difference between the observed and expected harvest fraction from the historical record for Egegik and Togiak from 1986-2010.

## Tables

**Table 2.1. Togiak Active Management Simulation Results.** The mean and CV of catch and escapement and the mean number of years above and below the ADF&G goal range for active management simulations (100 simulations) on the Togiak fishery from 1986-2010.

$ET_{early}$	$ET_{late}$	$m$	Mean catch	CV catch	Mean escapement	CV escapement	Number of years below ADF&G goal range	Number of years above ADF&G goal range
-3	-20	9	487 533	0.47	185 565	0.34	2.99	3.50
-1	-21	10	480 108	0.48	193 716	0.31	1.03	4.26
-2	-33	11	482 598	0.49	192 679	0.31	0.03	4.62
-2	-45	11	482 188	0.48	193 057	0.31	0.03	4.54
-2	-33	12	480 988	0.49	194 164	0.31	0.01	4.53

**Table 2.2. Egegik Fixed Fishing Schedule Simulation Results.** The mean and CV of catch and escapement and the mean number of years above and below the ADF&G goal range for fixed fishing schedule simulations (100 simulations) on the Egegik fishery from 1986-2010.

Days/wk	Mean catch	CV catch	Mean escapement	CV escapement	Number of years below ADF&G goal range	Number of years above ADF&G goal range
<b>Variable effort</b>						
M	2 546 481	0.58	4 863 017	0.44	0.00	25.0
M, F	4 919 802	0.56	3 467 028	0.38	0.00	24.1
M, W, F	6 224 347	0.52	2 618 788	0.40	0.00	21.2
M, T, Th, F	7 391 940	0.50	1 870 099	0.36	0.96	18.9
M, W, F, Sa	7 273 023	0.51	1 942 799	0.40	0.72	18.2
M, T, Th, F, Sa	8 121 677	0.49	1 322 678	0.33	3.88	10.8
M, T, W, Th, F, Sa	8 542 668	0.48	1 032 409	0.36	7.81	5.05
Everyday	8 948 707	0.47	713 805	0.31	15.8	0.03
<b>Constant effort</b>						
M	2 280 304	0.50	5 305 164	0.48	0.00	25.0
M, F	4 423 979	0.49	4 031 360	0.45	0.00	24.4
M, W, F	5 755 953	0.47	3 167 238	0.45	0.00	22.9
M, T, Th, F	6 880 539	0.46	2 447 255	0.46	0.05	21.0
M, W, F, Sa	6 855 658	0.47	2 434 679	0.43	0.05	20.7
M, T, Th, F, Sa	7 707 589	0.46	1 826 021	0.42	1.30	17.3
M, T, W, Th, F, Sa	8 223 447	0.46	1 464 627	0.44	3.58	12.0
Everyday	8 710 087	0.46	1 081 319	0.40	7.03	4.95

**Table 2.3. Simulation Results by Management Strategy and Fishing District.** The mean and CV of catch and escapement and the number of years above and below the ADF&G goal range for historical and simulated fishing schedules (mean of 1 000 simulations) on the Egegik and Togiak fisheries from 1986-2010.

Fishing schedule	Mean catch	CV catch	Mean escapement	CV escapement	Number of years below ADF&G goal range	Number of years above ADF&G goal range
<b>Egegik</b>						
Historical	8 205 451	0.52	1 412 116	0.31	0	11
Active management	8 003 808	0.53	1 358 848	0.29	0.42	8.90
Fixed/variable effort	7 396 366	0.50	1 866 262	0.36	0.96	18.8
Fixed/constant effort	7 705 015	0.46	1 828 427	0.42	1.32	17.2
<b>Togiak</b>						
Historical	495 776	0.45	202 496	0.33	1	8
Fixed	462 033	0.40	200 447	0.37	2.01	8.40
Active management	482 301	0.49	192 914	0.31	0.08	4.59

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## Conclusions

Despite the Egegik and Togiak fisheries both being located in Bristol Bay, Alaska and each having one major river that sockeye salmon return to (the Egegik and Togiak Rivers, respectively), other attributes of the two fisheries vary greatly. The estimated Egegik run was generally larger, earlier, more condensed temporally, and more variable than the Togiak run. The Egegik fishery is managed by emergency order openings ("active management"), whereas the Togiak fishery is managed by a fixed fishing schedule to the extent practical. The Egegik fishery had a much higher drift gillnet effort than the Togiak fishery. Drift gillnet vessels can transfer into the Egegik fishing district during peak season with only a 48-hour penalty of not fishing, whereas the Togiak district has an exclusivity policy that says drift vessels that register for the Togiak fishing district cannot fish in any other fishing districts and vessels that register for other districts cannot switch to the Togiak district during peak season (State of Alaska 2010). The Egegik drift fleet was estimated to catch a smaller fraction of the fish than the Togiak fleet at a given effort level. However, the Egegik drift gillnet fleet tended to have a higher estimated harvest fraction than Togiak due to higher drift effort.

This thesis shows that both active management and a fixed fishing schedule can be successful. Benefits of active management are higher mean catch and more control over escapement; however, this management is more expensive and requires more up-to-date information. Benefits of a fixed fishing schedule are less yearly variation in catch and a harvest spread more evenly throughout the season;

however, overharvest is more likely. This more temporally even harvest rate better protects substocks and the sex ratio.

Active management would be a desirable strategy for fisheries that are managed for MSY, have high fishing effort, a small fishing area, or a more temporally compressed run. Fisheries with high effort and a small fishing area are more likely to be overfished and active management is more likely to prevent overfishing. Active management is more likely to meet MSY than a fixed fishing schedule. If the run is more temporally compressed, a higher harvest rate may be needed to catch enough fish to keep escapement below the upper end of the goal range and enhance the ex-vessel value of the fishery.

A fixed fishing schedule would be a desirable strategy for fisheries with less intense effort, budgetary or efficiency concerns, or stock components that differ in run timing. In low-value, low-effort fisheries, the added cost of active management might not be offset by additional catch. If there are severe constraints in the management budget, a fixed fishing schedule can provide a satisfactory outcome even in areas better suited to active management, as we have shown for Egegik. A fixed fishing schedule provides more predictability for fishermen and processors than active management and can improve the profitability of the fishery (Steiner et al. 2011).

The management strategies used in Egegik and Togiak are appropriate given the attributes of each fishery. Active management is an appropriate choice for the Egegik fishery because the goal of the Egegik fishery is to maximize harvest while

meeting the escapement goal. The Egegik fishery has high effort and a small fishing area, making overharvest more likely, and a more temporally compressed run. A fixed fishing schedule is an appropriate choice for the Togiak fishery because it increases the efficiency of processors and individual fishermen, while the exclusivity policy keeps effort more constant and reduces the likelihood of overfishing.

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